

High-Pressure Compaction and Baling of Solid Waste

Bureau of Solid Waste Management

prepared for

Environmental Protection Agency

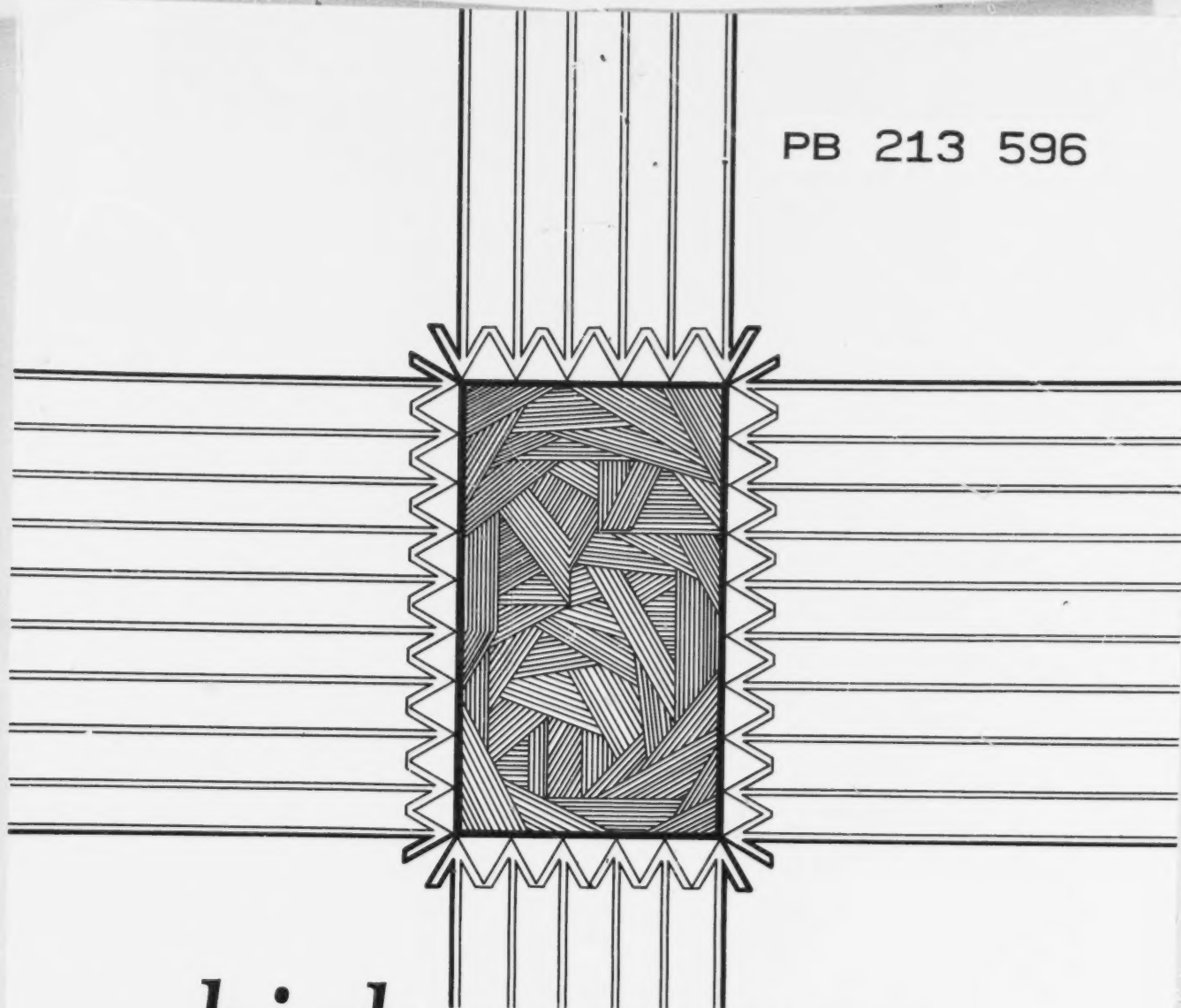
1972

Distributed By:

NTIS

**National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151**

PB 213 596



high-pressure compaction & baling of solid waste

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

This report has been reviewed by the U.S. Environmental Protection Agency and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of commercial products constitute endorsement or recommendation for use by the U.S. Government.

high-pressure compaction & baling of solid waste

final report on a solid waste management demonstration grant

Chapter I of this report (SW-32d) was prepared by the National Bureau of Standards and the Office of Solid Waste Management Programs, with the cooperation of the American Public Works Association. Chapters II through V, on work performed under solid waste management demonstration grant no. D01-UI-00170 to the American Public Works Association, were prepared by KARL W. WOLF and CHRISTINE H. SOSNOVSKY and are reproduced as received from the grantee.

U.S. ENVIRONMENTAL PROTECTION AGENCY

1972

I

*An environmental protection publication
in the solid waste management series (SW-32d).*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price \$1.75

FOREWORD

Some 75 years ago, American humorist and social critic Mark Twain described an industrial city on the Mississippi as a "soot-blackened town." A little more than a decade later, Theodore Roosevelt admonished the Nation in a message to Congress not "...to waste, to destroy, our natural resources, to skin and exhaust the land...." Today, Twain could add that his "monstrous big river" is umber-colored with the wastes it carries, and Roosevelt could look out on landscape that is defaced and often spoiled by the wastes deposited on it.

In the intervening years of unprecedented national growth, reflected in increased population, expanding municipalities, and greater industrial and commercial opportunities, we have responded with nonconcern to a concurrent physical deterioration of the United States. The first comprehensive water pollution control legislation was not enacted until 1956; the first comprehensive air pollution legislation, in 1963. Finally, less than six years ago, legislation acknowledged a national solid waste problem—a pollution that can pervade the air, water, and land.

Under the Solid Waste Disposal Act of 1965 (Title II, PL 89-272) and now under the broader mandate of the Resource Recovery Act of 1970 (PL 91-512),

municipalities and other nonprofit agencies are eligible to apply for Federal demonstration grants to study, test, and demonstrate techniques which advance the state of the art in the solid waste management field.

Some disquieting statistics compiled by the Office of Solid Waste Management Programs point up the significance of these demonstration projects. The Nation's annual outlay for getting rid of its debris is \$4.5 billion—and growing. Most of this is expended for collecting only 180 million tons of the 360 million tons of household, commercial, and industrial waste actually generated and disposing of it through predominantly unsatisfactory landfill or incinerator operations. Ninety-four percent of land disposal operations consist of open burning dumps that add to air pollution, or contaminate ground water and contribute to water pollution—or both; 75 percent of the incinerators burning municipal waste lack acceptable air pollution control equipment.

This publication reports on a study and investigation of an integral process in an alternative transport and disposal system that, potentially, could alleviate waste disposal problems encountered in large metropolitan areas.

SAMUEL HALE, JR.
Deputy Assistant Administrator
for Solid Waste Management

PREFACE

In grappling with solid waste management problems that worsen daily, public officials in many major cities, unable to find sufficient land within trucking distance, are considering using the railroad to carry solid waste materials to outlying strip mines or other spoiled lands. There, sanitary landfill techniques could provide for a successful solid waste disposal project as well as a construction project to reclaim the lands.

To promote economical transportation costs, efficient handling, and longer sanitary landfill life, compacting the collected wastes into tight, dense bales that stay intact over long distances may be an advisable intermediate step. Additionally, and quite important, compaction and baling techniques may provide the refinement needed to assure that neither environmental health nor public sensitivities will be assaulted, and engender the cooperation between the urban and rural areas which most experts realize will be essential in the long-term solution of solid waste problems.

By the year 2000, population in the United States is projected to double. Most of the increase is expected to collect in already sprawling metropolitan areas and their suburban satellites. Even now, in terms of amounts of wastes generated and spatial concentration, big cities are troubled most by the disposal problem. A sanitation official in Chicago--the site of this compaction and baling study--interviewed in the *Wall Street Journal* indicated that, with nearly all of the accessible open acreage around

the city already consumed, city planners are scrambling to identify acceptable alternatives to the present system which involves incineration and nearby land disposal sites. Change the name and Chicago could be any one of numerous metropolises across the Nation who may have to look to amenable outlying localities for sanitary landfill sites.

Because the baling-rail haul concept offers one solution to urban solid waste transport-disposal problems, this Office has financially supported a rail-haul feasibility study, being conducted by APWA, and this complementary compacting and baling study carried out by the City of Chicago. Not enough is known about the actual methods, the hazards, possible causes of failure and economics of the rail haul concept. The type of railroad cars, the kind of equipment to be used, the presses, the kind of binding, the stability of the final product, its weight and volume, the behavior of the waste before and after compaction, its density and volume reduction--these are only some of the questions that were considered in this study.

James J. McDonough served as the Project Director for the City of Chicago while R. Kent Anderson served as the Project Officer for the Division of Demonstration Operations.

We hope this report on initial experiments on compacting and baling of residential solid waste materials will afford some basic insights into this relatively recent innovation in solid waste processing.

JOHN T. TALTY, Director
Division of Demonstration Operations
Office of Solid Waste Management Programs

ACKNOWLEDGMENT

To develop the findings presented in this report required the cooperation of many people. First and foremost, recognition is given to the Director of the project, James J. McDonough, Commissioner, Department of Streets and Sanitation, City of Chicago, and to Deputy Commissioner Theodore C. Eppig. It would have been impossible to carry out a project of so complex a nature without their unfailing guidance, support and encouragement.

Furthermore, recognition is given to James V. Fitzpatrick, the predecessor of Commissioner McDonough, who was responsible for the inauguration and the initial planning and development of this project.

Acknowledgment is made to the research assistance provided by: Professor V. J. McDonald, University of Illinois, Urbana, Illinois; L. A. Finlayson and C. K. Cole, IIT Research Institute, Chicago, Illinois; Edward A. Janulionis, D and J Press Co., Inc., North

Tonawanda, New York; George J. Hartman, Farrel Corporation, Metals Press Division, Rochester, New York; Joseph F. Majers, Acme Products Division, Interlake Steel Corporation, Chicago, Illinois; The Technical Center, Penn Central Railroad, Cleveland, Ohio. The contributions made by these persons, personnel of the City's Department of Streets and Sanitation, Department of Public Works, and Department of Public Health, members of the APWA Staff, and the many other people who have worked on the project are deeply appreciated. Furthermore many persons reviewed the drafts of the report with great care. Their comments have been invaluable in the finalization of the report.

Finally, special acknowledgment is due Dr. Karl W. Wolf and Dr. Christine H. Sosnovsky—the principal investigators for the project and authors of this report.

SAMUEL S. BAXTER, Chairman
American Public Works Association
Research Foundation

CONTENTS

CHAPTER I. INTRODUCTION, SUMMARY, AND CONCLUSIONS	1
CHAPTER II. THE BASIC FRAMEWORK OF THE PROJECT	11
<i>Section One. Project background</i>	11
<i>Section Two. Project objectives</i>	11
<i>Section Three. Guidelines underlying the project execution</i>	12
I. The framework for the basic study approach, 12	
II. Process performance parameters of high-pressure compaction in terms of solid waste rail haul, 12	
1. Process performance requirements in terms of material input, 12	
2. Process performance requirements in terms of material throughput, 13	
3. Process performance requirements in terms of material output, 14	
a. Material density, 14	
b. Form and shape of the output, 16	
c. Size of the bales, 17	
d. Stability of the bales, 18	
4. Process performance requirements in terms of public health and environmental control, 19	
5. Process performance requirements in terms of cost, 19	
III. Implications of process performance requirements for the selection of the research press, 19	
1. Selection of the basic type of compaction equipment, 19	
2. Selection of the compaction equipment by speed of pressure application, 20	
3. Selection of the compaction equipment by size, 20	
a. Dimensions of the compaction chamber, 20	
b. Volume reduction potential, 23	
IV. Summary of the operational guidelines underlying the execution of this project, 23	
CHAPTER III. THE HIGH-PRESSURE COMPACTION OF SOLID WASTE MATERIALS	25
<i>Section One. Experimental setup, procedure, and measurement development</i>	25
I. Experimental setup and procedure, 25	
1. Compaction press, 25	
2. Press operation, 27	
3. Measurement of press parameters, 27	
4. Calibration of the deflection and pressure measuring system, 28	

II.	Development of methods for the measurement of forces at the bale-press interface and within the bale, 28	
1.	Measurements within the bale, 29	
2.	Measurements of forces at the press chamber walls, 29	
3.	Chamber wall measurements using penetration gages, 32	
Section Two. Description of the solid wastes used in the study		33
I.	Residential refuse, 33	
1.	Composition and moisture content of loose, sacked, and shredded residential wastes, 33	
a.	Composition of winter and spring refuse, 33	
b.	Moisture content of loose and sacked residential refuse, 34	
c.	Moisture content of shredded residential wastes, 34	
2.	Densities of loose, sacked, and shredded residential wastes, 36	
3.	Composition, moisture content, and densities of oversized wastes, 37	
II.	Synthetic samples of residential wastes, 37	
1.	Synthetic residential waste mixtures, 37	
a.	Composition, 37	
b.	Moisture content, 37	
c.	Densities, 39	
2.	Synthetic samples of paper and water, 39	
a.	Composition, 39	
b.	Absorbed moisture in papers, 39	
3.	Synthetic samples of papers and adhesive, 41	
4.	Selected samples containing one or several known refuse components, 41	
Section Three. Compaction of refuse		41
I.	Procedure, 41	
II.	Compaction of residential wastes, 43	
1.	Residential refuse-loose, 43	
a.	Volume reduction during compaction, 43	
b.	Effect of incoming densities on volume reduction, 44	
c.	Changes in volume and bale formation during final compaction, 46	
d.	Effect of springback forces and pressure holding time on bale volume during compaction, 47	
e.	Bale densities during high-pressure compaction, 48	
f.	Weight losses during compaction, 51	
g.	Properties of leachings released during compaction, 51	
h.	Volume expansion of bales after compaction, 53	
i.	Densities of bales after volume expansion, 55	
j.	Effect of pressure holding time and moisture content on the stability of bales after compaction, 56	
2.	Paper-sacked and plastic-sacked residential wastes, 57	
a.	Volume reduction during compaction, 58	
b.	Bale densities during compaction, 58	
c.	Volume expansion and bale densities after compaction, 58	
d.	Effect of adhesives on volume reduction ratio and bale densities during and after compaction, 58	
e.	Effect of pressure holding time and refuse properties on the stability of bales of sacked refuse, 59	
3.	Shredded residential wastes, 59	
a.	Volume reduction during compaction, 59	
b.	Bale densities during high-pressure compaction, 60	
c.	Volume expansion of bales and bale densities after compaction, 60	

- d. Effect of pressure, moisture content, and pressure holding time on bale stability, 62
- 4. Gas development in residential waste bales, 62
- III. Compaction of synthetic refuse samples, 64
 - 1. Synthetic refuse mixtures—loose, 64
 - a. Effect of pressure on bale volume during compaction, 64
 - b. Effect of pressure holding time on bale volume during compaction, 64
 - c. Volume expansion of bales after compaction, 64
 - 2. Synthetic mixtures in paper sacks, 67
 - a. Effect of pressure and pressure holding time on bale volume during compaction, 68
 - b. Volume expansion and bale stability of paper-sacked synthetic refuse, 68
 - 3. Synthetic paper-water samples: moisture experiments, 69
 - a. Effect of moisture on bale volume during compaction, 70
 - b. Volume expansion after compaction as a function of moisture content, 71
 - c. Stability of different paper-water samples, 71
 - 4. Synthetic samples of papers and adhesives, 72
 - 5. Compaction properties of selected refuse components, 73
 - 6. Measurements of load distribution during compaction of synthetic mixtures and other refuse samples, 73

CHAPTER IV. THE STABILITY OF SOLID WASTE BALES IN TERMS OF RAIL-HAUL SYSTEMS 87

Section One. Basic stability factors and concepts 87

Section Two. Stability test considerations 87

- I. Bale stability in terms of rail transport, 87
 - 1. Longitudinal shock and vibration, 87
 - 2. Lateral shock and vibration, 89
 - 3. Vertical shock and vibration, 89
 - 4. Travel distance and time, 90
- II. Bale stability in terms of material handling, 90
- III. Bale stability in terms of bale storage and shelf life, 90
- IV. Test selection with respect to bale stability required for solid waste rail-haul systems, 91

Section Three. Vibration and impact tests made under laboratory-scale conditions involving 12 bales with widely varying characteristics 91

- I. Test setup, 91
 - 1. Test equipment and basic test procedure, 91
 - 2. Bale sample, 92
- II. Test results, 93
- III. Conclusions, 93

Section Four. First 700-mile rail test shipment involving 40 bales with selected characteristics 104

- I. Test setup, 104
 - 1. Rail equipment; transport distance, and route, 104
 - 2. Bale sample, 104
 - 3. Loading configuration, 105
- II. Test execution and results, 105
- III. Conclusions, 110

<i>Section Five. Second 700-mile rail test shipment involving 264 bales with selected characteristics</i>	119
I. Test setup, 119	
1. Rail equipment, transport distance, and route, 119	
2. Bale sample, 119	
3. Loading configuration, 119	
II. Test execution and results, 119	
III. Conclusions, 123	
<i>Section Six. Drop test series covering, in 18 tests, 46 bales with varying characteristics</i>	128
<i>Section Seven. Observation of bale properties during the numerous bale-handling operations required at the test site</i>	128
<i>Section Eight. Major conclusions on the stability of compacted solid waste bales</i>	128
 CHAPTER V. THE IMPLICATIONS OF APPLYING HIGH-PRESSURE COMPACTION TO SOLID WASTES FOR RAIL HAUL AND SOLID WASTE DISPOSAL	135
<i>Section One. Development of compaction equipment performance specifications</i>	135
I. Guidelines for the investigation of alternate compaction equipment specifications, 135	
II. Press capacity considerations, 136	
1. Press productivity and bale size, material density, rate of bale production, 136	
2. Effects of pressure hold time on production, 136	
3. Options concerning bale size and compaction rates in terms of varying production requirements per 8-hour shift, 138	
4. Press capacity in terms of transfer stations for rail haul, 140	
a. 50 tons per 8-hour shift capacity, 140	
b. 100 tons per 8-hour shift capacity, 142	
c. 250 tons per 8-hour shift capacity, 142	
d. 500 tons per 8-hour shift capacity, 142	
5. Conclusions, 142	
III. Hydraulic pressure considerations, 142	
1. Availability of hydraulic components and parts, 142	
2. Relationship between diameter of hydraulic cylinder and variations in pressure applied, 143	
3. Utilization of hydraulic forces in compaction of solid wastes, 143	
IV. Press design considerations concerning press loading, the charging box, and the geometric shape of the compaction chamber, 145	
1. Loading of the press, 146	
2. Charging box, 146	
3. Geometric shape of the compaction chamber, 147	
V. Press design considerations concerning the press frame, 147	
1. Press frame in terms of solid waste compaction, 147	
2. Basic considerations for a minimum-weight frame, 148	
3. Description of an existing single-axis lightweight press frame (IITRI), 148	
4. Application of the lightweight frame concept to multiple-axis compacting, 149	
5. Effects of compaction chamber dimensions on the press frame, 150	
6. Operational life of the press frame, 152	
VI. Considerations on press foundations, 153	

<i>Section Two. Selected compaction equipment performance specifications</i>	154
<i>Section Three. Prices and construction cost estimates for hydraulic presses potentially suitable for the high-pressure compaction of solid wastes</i>	155
I. Data limitations,	155
II. Prices and cost of existing hydraulic presses,	156
III. Cost estimates for a lightweight-frame solid waste compaction press,	156
<i>Section Four. Implications of the high-pressure compaction of solid wastes with respect to rail haul</i>	160
I. Overall public health and environmental control aspects,	160
II. Implications with respect to transfer stations,	160
1. Foundations,	160
2. Pretreatment of the solid waste input materials,	160
3. Press loading equipment,	160
4. Handling of the bales,	161
5. Storage of bales,	161
6. Public health and environmental control,	161
7. Cost,	161
III. Implications with respect to rail transport,	161
1. Bale loading configurations,	161
2. Rail car design,	161
3. Transport operations, distance, and routing,	162
IV. Implications with respect to sanitary landfills,	162
1. Basic construction of sanitary landfills for the disposal of solid waste bales,	162
2. Operations of landfills for solid waste bales,	162
3. Public health and environmental control measures,	162
V. Conclusions,	163
<i>Section Five. Outlook</i>	163

INDEX TO TABLES

Table	Title	Page
1	Conversion of Transfer Station Throughput into Compaction Process Throughput, Expressed in Tons per Minute and Assuming Variations in the Actual Working Time As Well As Selected Levels of Productivity and/or Press Utilization	13
2	Range of Purchase Prices for Standard Rail Freight Cars by Load Carrying Capacity	14
3	Approximate Material Density Alternatives Given by the Dimensions of Selected 100 Ton Standard Rail Freight Cars	17
4	Approximate Patterns for Various Bale Sizes as Suggested by Rail Freight Car Loading Constraints	18
5	The Weight of Solid-Waste Bales in Terms of 360 Minutes Effective Press Operations, Varying Overall Throughput Requirements, and Variations in the Number of Bales Produced per Minute	21
6	Bale Volumes Corresponding to Variations in Selected Bale Dimensions Derived from Rail Car Loading Dimensions	21
7	Calculated Density Patterns Expressed in Pounds Per Cubic Foot and Based Upon Variations in Bale Volume and Bale Weight as Suggested by Solid-Waste Rail-Haul Operating Parameters	22
8	Compaction Chamber-Bale Volumes Based on Various Amounts of Springback	23
9	Composition of Dry Winter Refuse	33
10	Composition of Spring Cleaning Refuse	34
11	Moisture in Residential Refuse	35
12	Moisture in Shredded Residential Refuse	35
13	Densities of Residential Refuse	36
14	Effect of Moisture on the Densities	36
15	Composition of Synthetic Refuse Mixtures (1) and (2)	38
16	Composition of Synthetic Paper Mixtures	39
17	Moisture in Papers	40
18	Volume Reduction Ratios During Compaction of Residential Refuse—Loose Compacted at about 3500 psi	44
19	Volume Reduction Ratios of Different Bales Compacted at Different Pressures	45
20	Volume Reduction Ratios of Loose Household Refuse as a Function of Incoming Densities and Compaction Pressures	45
21	Densities of Bales of Residential Refuse, as a Function of Incoming Densities and Compaction Pressures	50
22	Volume of Bales Compacted at 3000 to 3500 psi for Loads of 200 Pounds Loose Refuse	51

Index to Tables (Continued)

23	Chemical Analysis of Leachings	52
24	Microbiological Analysis of Leachings	54
25	Volume Expansion of Bales after Compaction	55
26	Densities of Bales after Volume Expansion	56
27	Volume Reduction Ratios of Paper- and Plastic-Sacked Residential Wastes During Compaction	57
28	Densities of Bales of Paper- and Plastic-Sacked Refuse During Compaction	57
29	Volume Reduction Ratios and Bale Densities of Paper-Sacked Residential Wastes During and After Compaction	58
30	Effect of Adhesives on Bale Densities and Volume Reduction Ratios for Paper-Sacked Household Refuse Compacted at Different Pressures	59
31	Volume Reduction Ratios of Different Samples of Shredded Refuse	60
32	Densities of Bales of Shredded Refuse During Compaction	61
33	Volume Reduction Ratios and Bale Densities of Shredded Refuse During and After Compaction	61
34	Volume Increase of Compacted Shredded Refuse with Time	62
35	Gas Analysis and Bale Temperature of Compacted Spring Cleaning Residential Wastes	63
36	Average Volume Reduction Ratios of Synthetic Refuse Mixtures	65
37	Volume Increase of Paper-Sacked Synthetic Refuse Bales after Compaction at Low Pressures	69
38	Typical Distribution of Impacts Occurring in a Railroad Classification Yard	88
39	Probability of Impact Occurrence in Sequential Switching Yards	89
40	Conbur Test	92
41	Selected Information on the Twelve Bales Used for the Vibration and Impact Tests Under Laboratory-Scale Conditions	94
42	Summary of Results from the Vibration and Impact Test Series Conducted Under Laboratory-Scale Conditions	95, 96
43	Composition of Bale Sample for First Rail Test Shipment	105
44	Incidences of Longitudinal Impacts on Test Car During Transport of Bales from Chicago to Cleveland in First Rail Test Shipment	110
45	Summary of Selected Information on the 264 Bales Subjected to the Second Rail Transport Test Covering a Travel Distance of More than 700 Miles	120
46	Weight of Bales Shipped in the Second Rail Transport Test	121
47	Incidence of Longitudinal Impacts on Test Car During Transport of Bales from Chicago to Cleveland in Second Rail Test Shipment	121
48	Selection of Local Climatological Data for Chicago, Illinois and Cleveland, Ohio For the Time Period April 28 to May 15, 1969	123
49	Summary of Drop Test Results	130, 131
50	Matrix of Press Capacity Alternatives Based on an Effective Production Time of 480 Minutes per 8-Hour Shift and on Variations in Overall Throughput, Size and Weight of Bale and Pressure Holding Time	139

Index to Tables (Continued)

51	Matrix of Press Capacity Alternatives Based on an Effective Production Time of 360 Minutes per 8-Hour Shift and on Variations in Overall Throughput, Size and Weight of Bale and Pressure Holding Time	141
52	Variations in the Total End-Frame Load-Bearing Requirements Resulting from Changes in the Length of the Compaction Chamber at a Load of 2000 psi Applied to the End-Frame and a Constant Chamber Volume	152
53	Summary of Economic Data on Hydraulic Presses Potentially Suitable for the Compaction of Solid Wastes	157
54	Estimated Lightweight Frame Weights for Single- and Double-Axis Solid-Waste Compactors, Based on Different Bale Sizes, Two Types of End Section Construction, A Cubic Configuration of the Bale in the Compaction Chamber, and an 18:1 Volume Reduction Ratio	158
55	Cost Estimates for Lightweight Solid-Waste Hydraulic Compaction Presses Based on Variations in Bale Sizes, End Sections, Ratios of Frame Weight to Total Weight, Number of Compaction Stages, and Material Cost	159

INDEX TO FIGURES

Figures	Title	Page
1	Compaction Rates for Various Levels of Productivity	15
2	Correlation Between Increase in Car Purchase Cost and Increase in Car Length for 100-Ton Box, Gondola and Flat Cars	16
3	Compaction Press	26
4	Electronic Measuring System Diagram	27
5	Penetrometer Gage	29
6	Strain Gaged Liner Plate	30
7	Response of Strain Gage to Loads from Various Materials	31
8	Penetration Gage Calibration Curve	32
9	Residential Wastes—Loose. Ram Deflection During High-Pressure Compaction	44
10	Volume—Pressure Relationship for High and Low Density Refuse	47
11	Residential Waste, Sequence of Ram Deflection for Loose Refuse Compacted Initially Up to 3500 psi (a) and then at 1150 psi (b, c, d)	49
12	Residential Wastes. Effect of Pressure Holding Time on Bale Height	49
13	Average Densities of Residential Wastes During and After Compaction	56
14	Synthetic Refuse—Loose. Decrease in Bale Height as a Function of Pressure	65
15	Decrease in Bale Height as a Function of Holding Time	66
16	Synthetic Refuse—Loose. Average Volume Increase of Both Mixtures With and Without Holding of Pressure	67
17	Synthetic Refuse—Loose. Volume Changes of Bales Compacted for 5 to 10 Minutes	68
18	Paper-Sacked Synthetic Refuse—Decrease in Bale Height During Compaction With and Without Holding of Pressure	69
19	Effect of Moisture Content on Bale Height During Compaction of Paper Samples Compacted at About 3500 psi	70
20	Increase in Density as a Function of Moisture Content	71
21	Volume Expansion of Compacted Paper Bales Containing 10 to 50 Weight Percent of Added Water	72
22	Total Load Distribution at Bottom and Top of Bales	74
23	Sample of Impact Register Chart Showing the Interpretation Standards	104
24	Illustration of the Bale Loading Configuration Used in the First Rail Test Shipment	106, 107
25	Example of Impact Recordings Made During the First Rail Test Shipment	108, 109
26	Record of Air Temperature in the Test Car During the Second Rail Test Shipment	122
27	The Interrelationship of Waste Compaction Tonnage and Compaction Rate for Various Bale Weights at Approximately 1 Ton Per Cubic Yard Density	137

Index to Figures (Continued)

28	The Influence of Pressure Hold Time on the Production Rate	138
29	Interrelationship Between Diameter of Hydraulic Cylinder, Hydraulic Pressure, and Pressure Applied for Two Sizes of Bales in the Compaction Chamber	144
30	Approximate Relationship Between Volume Reduction and Pressure Applied for Maximum 2,000 and 3,000 psi Applied Pressure Systems	145
31	Concept of the Geometry of the IITRI Lightweight Press Frame	149
32	Configuration of the Compaction Chamber	150
33	Selected Interrelationship Between Length of Compaction Chamber and the End Load Restraining Forces Required for Chamber Volume of Eight Cubic Feet	151

INDEX TO PHOTOGRAPHS

Compaction of Solid Wastes	76
Compaction of Loose and Paper-Sacked Residential Wastes	77
Individual Bales Compacted at About 3500 psi	78
Compacted Winter Refuse—Loose and Paper-Sacked	79
Bales Compacted at About 2000 psi	80
Bales, Various	81, 82, 83, 84
Compacted Bales After Handling and Relatively Long Term Exposure to Weather Conditions	85
Test No. 1	97
Test No. 2	98
Test No. 3	99
Test No. 4	100
Test No. 5	101
Test No. 6	102
Test No. 7	103
Boxcar Used for Rail Test Shipment	111
Bales Loaded with Sand Bags	112
Bracing of Bales Before Shipment	113, 114
Condition of Load After Return to Chicago	115, 116, 117
Bales on Truck After Unloading	118
Bales Before Second Test	124
Condition of Load After Return to Chicago	125, 126, 127
Tests No. 9 and No. 8	132
Tests No. 10 and 12	132
Tests No. 13 and No. 11	133

CHAPTER I

INTRODUCTION, SUMMARY, AND CONCLUSIONS

1. INTRODUCTION

This report documents some initial experiments in this country on the high-pressure compaction of municipally collected solid wastes. The American Public Works Association (APWA) Research Foundation performed the work for the City of Chicago under a Federal demonstration grant from the Bureau of Solid Waste Management (BSWM*), of the Department of Health, Education, and Welfare (HEW).

The BSWM prepared this introductory chapter jointly with the Technical Analysis Division and Product Evaluation Technology Division of the National Bureau of Standards. The remainder of the report (Chapters II through V) is reprinted as written for the City of Chicago by the APWA Research Foundation.

The compaction and baling study is an outgrowth of another demonstration grant project conducted by the APWA for HEW and many local government jurisdictions in the United States and Canada. This demonstration grant studied the potential benefits of rail haul in solid waste disposal systems.** A short series of spot tests performed during the rail-haul study had indicated that the high-pressure compaction of municipal solid wastes was feasible and could contribute substantially to the concept of the rail-haul of solid wastes away from the urban environment. These preliminary tests also showed, however, that additional testing was needed to: (1) expand the preliminary test results; (2) investigate more thoroughly significant parameters in the high-pressure compaction of solid wastes; (3) determine the operational implications of this promising approach to solid waste processing.

With the help of APWA, the City of Chicago prepared and submitted an application for a three-phase grant to BSWM which proposed that:

"The ultimate objective of this project is to determine the optimum requirements for the design of suitable production-scale equipment to compress solid wastes into high-density economical payloads for transport by rail and to test the operational aspects of such a system."

*Now the Office of Solid Waste Management Programs of the U.S. Environmental Protection Agency (EPA).

**Demonstration Grant No. G06-EC-00073, "Investigate the Potential Benefits of Rail-Haul as an Integral Part of Waste Disposal Systems."

The main objective of the first phase, reported on here, was:

"...to obtain (production-scale) information on the various parameters which affect the compaction of refuse into bales readily handleable after compaction."

The first year's program was to be designed:

"...to provide reliable information to permit the development of performance specifications for production-scale compaction (equipment). This would involve the use of an experimental press equipped with a number of interchangeable parts so that the effects of various press variables on the compaction of refuse of different characteristics can be determined."

Eighteen secondary objectives were listed:

"...to dimension the advantages and disadvantages of various bale sizes with respect to compression and/or baling;

...to determine the number and positioning of the strokes needed to produce suitable bales;

...to investigate alternatives which would reduce the stroke requirements while enhancing the baling; e.g., the utilization of pressure- or spring-controlled counter-pressure plates; time and throughput are of considerable concern since rail-haul deals with operations typical for mass production.

...to ascertain the feasibility, parameters, and operating requirements of extrusion;

...to measure the influence of variations in the pressure applied in general and within the framework of varying stroke arrangements;

...to analyze the impact of production cycle times and of the speed of compression;

...to investigate the production and handling parameters of varying bale configurations;

...to determine the workability of production-scale operations concerning bales of exact volume, exact weight, or exact density;

...to establish design criteria for the feeding devices needed;

...to evaluate the stability of bales of different sizes and configurations;

...to ascertain the influence and behavior of selected types of refuse and refuse compositions under various pressures applied and within the framework of bale and press variations;

...to develop workable solutions for solving the moisture problem;

...to investigate the possibilities of achieving public health and total environmental control safeguards for the rail-haul system through the compression or associated operations;

...to arrange for the necessary biological and chemical bale sample analysis with appropriate departments of the U.S. Public Health Service;

...to specify the fail-safe provisions needed for full-scale operations;

...to calculate the techno-economic parameters resulting from varying approaches to production-scale operations;

...identify the instrumentation and controls needed for full-scale operations; and,

...to establish design criteria and performance specifications which can be released to various equipment manufacturers in order to foster competition and enlist the industrial development capabilities for the benefit of the rail-haul systems."

From the outset, the program—an ambitious undertaking—encountered difficulties, particularly in obtaining an experimental press with interchangeable parts. Finally, a 17-year-old, three-stroke metal scrap baler, donated by General Motors Corporation, was modified and installed in a Solid Waste Research Facility built by the City of Chicago. In practice, the only press variables that could be studied were applied pressure in one direction (after a gathering of the load by the machine into a volume with fixed rectangular cross-section perpendicular to the direction of applied pressure) and the length of time the pressure was held. Only one configuration and roughly one size range of bale was possible (16 inches by 20 inches by variable 14 to 18 inches), in the form of a rectangular parallelepiped.

In Section 2, a fairly elaborate summary of the report is given. This includes only the major results.

2. SUMMARY OF THE REPORT

Chapter II (pages 11-24) is entitled, "The Basic Framework of the Project." The first two sections discuss the project background and project objectives. This is followed by the development of guidelines by APWA for the execution of this investigation. This is an attempt to take into account the comprehensive objectives of the project in light of the tight constraints of manpower, time, and funds. In developing these guidelines, consideration was given to process performance requirements in terms of material input, throughput, and output. For the latter, there are discussions relating to the output density (pp. 14-15) form, shape, size, and stability of the bales produced (pp. 16-19); requirements in terms of cost, public health, and environmental control (p. 19) are

also discussed briefly. Funding and time limitations eliminated the possibility of building a compaction device specifically designed for this research project. The implications of these process performance requirements of input, throughput, and output were then taken into consideration in seeking a press for the research project (pp. 19-23). Details of the actual press used are given in Chapter III (p. 25). The operational guidelines developed by APWA are given on pages 23 and 24 of the report and are also reproduced here:

1. Confine the compression tests to residential solid waste mixtures and their components.
2. Base the process developments on material throughput or capacity ratings of 0.14 to 1.4 tons per minute.
3. Try to achieve average material shipment densities of at least 50 pounds per cubic foot.
4. Avoid the investigation of very low or very high pressure applications, if they do not relate to the volume reduction or stability requirements of this project.
5. Give priority to the development of square or rectangular bales. Consider other configurations only in case of need.
6. Limit the developments to a maximum of four ultimate bale sizes—one of their sides being 1.12, 1.50, 2.25 or 3.00 feet. If necessary, concentrate the research efforts on the 1.50- and 2.25-foot bale.
7. Determine carefully the amount and, in particular, any directional orientation of springback occurring in the bales after exit from the press.
8. Develop bales which are stable for 9 days and suitable for rail transport of up to 150 miles within this time period.
9. Emphasize the application of pressure for achieving bale stability. Investigate other stability aids only in case of need.
10. Check for pollution caused by the compaction process itself. Engage in pollution control research if compaction by itself causes any form of pollution which cannot be handled in an acceptable manner by existing control methods.
11. Orient all investigations toward the establishment of a compaction process of minimum cost. Investigate specifically avenues of possible equipment development which promise cost reductions and thereby will foster a more widespread application of the high-pressure compaction process.
12. Obtain a hydraulic press which:
 - (a) is capable of applying relevant pressures upwards of 2,500 pounds per square inch within a time span of less than 30 seconds to solid waste materials in an enclosed chamber;

- (b) has dimensions of its compaction chamber which can support an extrapolation of the test results to compaction chamber dimensions ranging from a minimum of 1.68 to 8.54 cubic feet to a maximum of 0.70 to 20.25 cubic feet;
- (c) provides an in-press volume reduction potential of at least 15.1.

Attention is called to the fact that these guidelines determine the scope as well as the depth of the project's total result. The press used also provided constraints upon the project which conditions some of the results. It was not possible to dimension the effects of these constraints in this initial effort; this research aspect is recommended for inclusion in any follow-up project (p. 24).

Note should be taken that since the press was out of order for one week, there was an actual testing time of only nine weeks (p. 11).

Chapter III (pp. 25-85) is entitled, "The High Pressure Compaction of Solid Waste Materials." The compaction experiments were carried out with a 17-year-old normal metal scrap baler which was reconditioned and modified. The modifications included an increase of the total force of the third ram and the addition of a series of ram locks to prevent the movement of the first and second low-pressure rams and the cover during the final high-pressure compaction. The first two rams operated in a horizontal plane and constituted a gathering of the refuse in the charging box into a rectangular parallelepiped with cross-section dimensions of 16 by 20 inches perpendicular to the vertical. In normal operation the cover was locked into position and, after gathering, and initial compaction by the first two rams, these rams were locked into position. The high-pressure ram was then operated in the vertical direction, usually until it reached a predetermined indicated gauge pressure, and the compaction was completed. To remove the bale from the press, all three rams were first moved slightly out of position to remove the pressure from the bale. After removal of the cover plate from the top of the box, the third ram was again activated to eject the finished bale out of the charging box (pp. 25-39). All of the bales produced were initially rectangular parallelepipeds (box shaped) with initial cross-section dimensions of 16 by 20 inches. The height of individual bales varied but was usually in the range of 14 to 18 inches.

An electronic measuring and recording system was installed to measure:

- (a) ram displacement of the intermediate ram;
- (b) hydraulic pressure of the high-pressure ram;
- (c) ram displacement of the high-pressure ram.

This system produced time-history records of the

event. Later a second output device was added to produce a direct plot of the applied pressure versus the displacement of the third ram. Examples of these charts, however, are not given in the report (pp. 27-28).

Attempts were made during the study to measure the forces active in bale formation. This is because a knowledge of the various forces developed in the press frame, at the bale interface, and within the bale are of importance both with respect to press design and for understanding of the compaction process. Existing techniques were utilized; but it was found that standard measuring techniques are not easily adaptable to refuse compaction and that new methods will have to be developed. An appreciable amount of work was done and several approaches were evaluated. One of the approaches showed great promise; it utilized penetration gauges for measurement at the interfaces between the chamber walls and the refuse. Although the application of the penetration gauge method could not be fully explored, the results indicate that useful information can be obtained from it. Contour drawings, not shown, were made of the load levels of the indentations produced during the compaction in the bottom and top plates. The total load distribution at the bottom and top of the bales is shown for different samples and different compaction conditions. The presented results show that peak loads can be developed both at the bottom bale face (resting on the high-pressure ram) and at the top of the bale. It is pointed out that at present it is not clear whether the peaking occurs primarily as a result of individual material properties of the bale components, or whether it is related to the compaction conditions. Further work in this direction is indicated (pp. 29-33, 73-75).

Two types of refuse (as delivered by truck), classified as winter and spring refuse, were examined in detail as to their contents. The winter refuse was largely composed of paper products with a range from about 50 to 80 percent by weight of the total refuse (p. 34). The refuse received from the City of Chicago during the spring period contained a large proportion of yard rakings and dirt, which were absent in the winter refuse. In addition, the spring refuse contained more glass, food, and metallic wastes but appreciably less paper. The composition, densities, and moisture content of loose and sacked residential refuse, of shredded (by a Heil-Gondard shredder) refuse received from Madison, Wisconsin, and of oversized wastes were also determined. Detailed results of these studies are presented in a tabular form (Tables 9-14, pp. 33-36). The densities of the incoming uncompacted waste samples ranged from 3.8 to about 15.9 pounds per cubic foot

depending primarily on different void proportions in the mixtures.

Synthetic samples of residential wastes were especially prepared for this study to test the effect of single waste components and mixtures on the compaction of wastes. Two large mixtures were especially prepared to simulate the composition of dry household refuse. Some samples were placed in paper sacks; others were used in loose state. To simulate overall liquid content of dry household refuse (as determined previously with the city-delivered refuse), liquids were either added separately or introduced through solid wastes containing bound or absorbed water (such as vegetables, fruit, and paper). A series of samples containing only paper products and a known amount of water was prepared in order to investigate the effects arising from the interaction of moisture and papers during and after compaction. In addition, several series of experiments were carried out to determine the moisture contained in papers before the addition of water (pp. 37-41).

A series of compaction experiments, using the converted three-stroke metal baler, was carried out on samples of the loose residential refuse, on the synthetically constructed samples, on synthetic mixtures to which adhesives had been added, and on specially secured refuse components. The pressure applied by the third ram was varied during individual compaction runs. The pressure applied by the third rams included 500, 750, 1000, 1500, 2000, 2500, 3000, and 3500 psi. A few samples were also compacted at higher pressures, about 6000 psi, by concentrating the available force of the high pressure ram on a smaller surface area. The experiments were exploratory in nature rather than statistically designed. As an example, the number of samples subjected to a particular indicated pressure, on a particular holding time of applied pressure, was not set in advance, but determined day by day from operating considerations. In some instances experiment levels (pressure, holding time, type sample) are "one of a kind." The recording equipment provided records of the variation of the applied pressure with time as well as the distance the ram moved during the pressure application. The time required to compact the bale in a so-called "normal fast run" was approximately 17 seconds. The decrease in volume was measured during compaction as a function of applied pressure. Subsequently, the expansion in volume of the compacted bales, outside the compaction chamber, was measured over a period of time (in some cases for 24 hours and longer). The densities of the compacted refuse during and after compaction were determined. The following are some of the principal results:

1. Changes in volume for samples of loose residential refuse:

- (a) The volume reduction during compaction of samples of similar density averaged about 13:1 at applied pressures of 3000 to 3500 psi and decreased systematically to about 9:1 at about 900 psi (Table 20 and pp. 44-46).
 - (b) The volume reduction ratio was higher if the density of the incoming refuse was lower and vice versa (Table 20, Figure 10, pp. 44-46).
 - (c) Holding of pressure during compaction always led to a decrease in bale volume (p. 47).
 - (d) Increase in pressure or increase in time of pressure application led to a decrease in bale volume during compaction, and to a reduction in expansion force after compaction (p. 47).
 - (e) An example (six different refuse samples prepared from the same load) shows that holding of pressure for either 5 or 10 minutes at about 1000, 1500, and 2000 psi led to the same approximate decrease in bale volume (p. 48 and Figure 12, curve b).
 - (f) From a series of 8 samples there is indication that the reduction in volume with time at low pressures is not of the same magnitude as that which can be achieved at highest pressures in fast runs (p. 48 and Figure 12).
2. For all kinds of samples, evaluation of recordings of the changes in ram deflection with time indicated that the maximum decrease was reached after less than one minute of pressure application (pp. 48, 64, 67, 68, and Figures 15 and 18).
3. For sacked residential refuse, synthetic loose refuse, and synthetic paper-sacked refuse the compacted volume reduction ratios were similar to those obtained with loose residential wastes of similar densities (p. 58, p. 64, and Tables 27 and 36).
4. An illustration of the effects of pressure holding time on bale volume during compaction for samples from one of the two mixtures of synthetic loose refuse shows that the decrease in bale height at about 850 to 1000 to 1500 psi was after holding of pressure, nearly equivalent to the decrease which was achieved by compaction in normal fast runs at a 700 psi higher pressure. At about 2000 to 2500 psi the decrease with time was nearly equivalent to that obtained in a fast run at about 500 psi higher pressure. Increase in pressure holding time from 5 to 10 minutes had no effect (p. 64 and Figure 15).
5. The major result with respect to volume and densities is that variations in the incoming densities of the different refuse loads had little effect on the density of the compacted bales. These

variations, however, did have an appreciable effect on the volume reduction ratio. As a result, refuse samples of the same volume produced bales of a large variety of sizes, whereas samples of the same weight produced bales of similar sizes. This finding suggests that control of the weight of the incoming refuse provides a better means for the controls of the compacted bale (p. 50).

6. The major results on springback of volume expansion are:

(a) Springback, or volume expansion, of the compacted bales starts immediately after the release of the compaction pressure (p. 53).

(b) Most of the springback takes place within the first 2 minutes; expansion during that time amounted to 50 to 60 percent of the original compacted volume (p. 53).

(c) The springback continues after the first 2 minutes at a slower rate. Bales stored individually and left to expand without any restriction, grew up to 95 percent larger than their original compacted volume (p. 55).

(d) The expansion of normal bales occurred preferentially, following the sequence of the three-step compaction process: least expansion occurred in the direction of the lowest pressure application, first ram movement; and the maximum expansion occurred in the direction of the highest pressure, third ram movement. This order of expansion was the same independent of the solid properties of the compacted refuse (p. 55).

7. Many observations are made with regard to the stability and appearance of bales after compaction (pp. 46, 56, 57, 59, 62, 67, 69, 71, 72, Chapter IV and p. 146). The principal results for loose residential waste are:

(a) The major factors found to affect the stability of compacted bales of loose residential wastes were compaction pressure, time of pressure application, and the moisture contents of the wastes (p. 56).

(b) In the absence of excessive moisture, compaction at high pressures resulted in the formation of stable bales. On the other hand, bales compacted at low pressures were quite fragile (p. 57).

(c) Fragile bales were usually obtained after compaction at pressures between about 500 and 1000 psi. These bales occasionally fell apart immediately after removal from the baler. Some fell apart after being handled successively several times. An improvement in stability was found for bales compacted at pressures between 1000 and 1500 psi. However, the stability of

most bales was markedly improved after compaction at 2000 psi and up to 3500 psi. A further increase in pressure, up to 6000 psi, produced no apparent improvement in bale stability (pp. 46, 57).

(d) The overall stability of the bales compacted at about 1000 and 1500 psi usually improved appreciably if the force on the bales was held for several minutes. The bales compacted at about 1000 psi for 5 minutes seemed to be as stable as those compacted at 1500 to 1750 psi without holding of pressure. Similarly, the bales compacted at about 1500 psi for 5 minutes appeared to have the stability properties of samples compacted at about 2000 psi without holding of pressure (p. 57).

(e) The stability of bales of very high moisture content was always poor, irrespective of the compaction pressure applied. There were, however, indications that the stability of the bales containing an appreciable amount of moisture could be improved if the compaction pressure were lowered (p. 57).

8. The compaction properties of a number of selected refuse components and mixtures were investigated. Some of the interesting results are:

(a) Rubber, plastic scrap, and food materials could not be compacted on their own.

(b) Mixtures of oversized wastes including bed springs, refrigerators, etc., produced excellent bales. (For a detailed listing see p. 73).

9. Special experiments were carried out to correlate moisture content to paper content, the major component of refuse mixtures (pp. 39, 40, Tables 16 and 17, pp. 69-72, Figures 19 and 20). Furthermore, papers exhibit pulping and expansion characteristics in the presence of moisture, and this determines to a large extent the compaction properties of residential waste mixtures. The major results of these compaction experiments are:

(a) A small amount of moisture has a beneficial effect on the compaction of residential wastes of high paper content (p. 69).

(b) The stability of all paper bales which contained a very large amount of moisture was found to be poor (p. 71).

(c) Most compacted bales of paper bundles were unstable irrespective of the moisture content (p. 71).

(d) Separated newspapers and paper mixtures, to which about 35 weight percent of water was added, were reasonably stable (p. 71).

10. A limited series of experiments (pp. 41, 42, 72) was carried out with paper mixtures to test the

effect of adhesives on bale stability and on the volume expansion of paper-sacked refuse and paper bales. The work with adhesives was not pursued further because the stability of the baled household refuse was found to be quite good without the use of adhesives. The major results on adhesives are:

- (a) Volume expansion was not substantially reduced by the addition of adhesives (p. 72).
- (b) The paper bale stability was distinctly improved by the addition of adhesives, and the appearance of the bales was excellent (p. 72).
- (c) The presence of adhesives sprayed on the outsides of samples each containing 10 bags of paper-sacked household refuse immediately before compaction had no effect on the compaction properties of wastes during compaction (pp. 58 and 59).

A small effort was expended to perform chemical and biological analyses of liquid compressed from the bale. The investigation was limited to a few tests, which were inadequate to assess the pollution potential of this liquid (pp. 52-54, Tables 23 and 24. See also pp. 62 and 63, Table 35 and pp. 160-163 for some related discussion on overall public health and environmental control aspects).

Chapter IV (pp. 87-133) is entitled, "The Stability of Solid Waste Bales in Terms of Rail-Haul Systems."

For current solid-waste rail-haul systems the bales should be capable of surviving a rail transport of at least 150 miles distance and of 3 to 6 hours duration of movement. During this travel the bales would be subjected to longitudinal, lateral, and vertical shocks and vibrations. The bales would be subjected to handling and possibly dropping at the transfer station and at the disposal site. Assuming a maximum 24-hour transport time and a once-a-week pickup, it is necessary that 9-day-old bales be suitably stable for rail-haul transport and for disposal site operations (pp. 87-90).

The first series of vibration and impact tests was carried out under laboratory conditions and involved bales of widely varying characteristics. Two sets of bales compacted at gauge pressures of about 2000 and 3500 psi were used. One set of bales was strapped and a corresponding set not strapped. The results indicated that all bales were exceedingly stable regardless of whether they were strapped or not, or whether they were compacted at the lower or higher pressures. All the bales exceeded the general stability specifications developed above. It was apparent that strapping improves the stability of the bales. However, since the unstrapped bales withstood the vibration and impact tests successfully, it was decided not to conduct additional strapping tests within the present project. It was also noted that a bale judged "good"

before testing tended, as a rule, to remain in this category after testing, and a bale judged "poor" still survived all the tests in this category (pp. 90-93, Tables 40, 41, 42, photographs: pp. 97-103).

Although the first stability tests were indeed positive, they nevertheless were made on a laboratory scale and were not fully representative of actual rail-haul conditions. Thus, two actual rail-haul tests were made with the car containing the compacted bales moved by regular freight trains. The transport distance exceeded 700 miles in each test shipment being made from Chicago to Cleveland and back and through three railroad yards. In each test the car was equipped with an impact recorder. In the second test, the car was also equipped with a humidity and a temperature recorder. In the first test, a sample of 40 bales made from regular Chicago household refuse as it came off the truck, were made up as follows: paper-sacked, compacted at 2000 and at 3500 psi; and loose, compacted at 2000 and at 3500 psi. None of the individual bales or the bale sets were strapped. None of the bales failed, i.e., broke apart, during the test. Two second-layer front bales which had fallen off and been thrown around in the car were only partially damaged. All the other bales were judged to be in very good condition, or at the very least, still in acceptable condition. All bales that were weighted down by either sand bags or other bales were judged to be in better condition than the bales not weighted down. The bales made from refuse in paper sacks appeared, as a rule, to be in better condition than bales made from loose refuse. Finally, there was a relatively small amount of spillage from bales made from loose refuse. There was no spillage from the paper-sack bales (pp. 104-110, photographs: pp. 111-118).

The second rail shipment test was set up similar to the first rail shipment test, except on a greatly enlarged scale. In this test, a sample of 264 bales was structured to contain an equal number of bales made from loose household refuse and from household refuse placed in paper sacks before compaction at gauge pressures of 1500, 2000, and 2500 psi. Each sub-group of samples was set up to include bales 6 to 8 days old at the outset of the test shipment. This test encountered transport conditions even more severe than those experienced in the first rail test shipment. Examination of the car in Cleveland by members of the Penn Central Railroad research staff showed that the bulkheads on one end of the car had collapsed and some bales had spilled into the center of the car. The bulkheads at the other end of the car were also damaged. However, all the bales were found to be in good condition; not one bale had disintegrated. Inspection after the return trip to Chicago showed that all bales came back intact. The amount

of spillage was estimated again as less than 1 percent of the total weight of the bales. Indications are that the bales produced a significant amount of heat and moisture, suggesting that some degradation of the organic constituent of the bales took place (pp. 119-123, photographs: pp. 124-127).

To study the effects of accidental dropping on bale stability, a series of 18 severe drop tests was carried out on 46 bales of varying characteristics. The test results show that solid waste bales which appear stable after exit from the press, are capable of taking a considerable beating from drop impacts. This holds true regardless of whether the bales are dropped individually or in groups. However, it appears that bales produced at higher compaction pressures are, as expected, more resistant to drop impacts than bales produced at low compaction pressures (p. 128).

Numerous observations on stability were made during the 10-week test period. These can be summarized as follows:

1. Bales that appear cohesive after exit from the press can be handled without special precautions.
2. Bales exhibiting apparently significant structural defects are still surprisingly strong in terms of the bale-handling operations performed.
3. Exposure of bales for about 3 weeks to outside weather conditions during February to May 1969 did not cause an appreciable amount of structural deterioration.
4. Spillage, as a rule, amounted to less than 1 percent of the weight of the bale.

Chapter V (pp. 135-163) is entitled, "The Implications of Applying High Pressure to Solid Wastes for Rail-Haul and Solid Waste Disposal." The implications of high-pressure compaction for the solid waste field are viewed primarily with respect to the development of compaction equipment performance specifications and the implementation of rail-haul systems (pp. 135, 160-162).

Compaction Equipment Implications:

1. The development of compaction equipment performance specifications was made in consideration of selected press design and operation parameters. The conceptual, technoeconomic analyses were confined to hydraulic presses (pp. 135-142, 154-160).
2. The press capacity analysis was based on one shift per day and 360 minutes effective operations per shift. This represents an efficiency equivalent of 75 percent of an 8-hour shift and of only 25 percent of a 24-hour per day capacity (pp. 140, 142).
3. In addition, the press capacity analysis takes into account variations in:

(a) throughput from 50 to 500 tons per shift;

(b) bale size from 0.25 to 1.0 cubic yard in the compaction chamber;

(c) rate of bale production from two bales per minute to one bale per 3 minutes;

(d) the pressure holding time ranging from 15 seconds to 1 minute (pp. 136-142).

4. Within this framework the analyses indicate a wide application potential for presses with a bale size of 0.50 or 0.75 cubic yard in the compaction chamber. The analyses suggest furthermore that transfer stations pegged at more than 250 tons per shift should have more than one press (p. 142).

5. The investigations of press hydraulics suggest that 3000 psi in hydraulic and 2000 psi in applied pressure, and a specified pressure holding time rather than higher pressures, should be preferred in the development of compaction equipment suitable for the rail-haul of solid wastes (pp. 142-145).

6. The charging box analysis indicates that an inclusion of over-sized wastes in the input mixtures does not create difficulties. The same analysis also suggests that the charging box cover be designed to perform an active function in the compaction process (pp. 145 and 146).

7. The press should be charged from the top by a batch system. In high-volume operations, it should not require more than 5 seconds to charge the load at a total cycle interval of 1 minute. The requirements are much less demanding in low-volume operations (pp. 146, 163).

8. Existing press frame construction techniques appear to be more than adequate for solid waste presses. In terms of operational life, the press frame should be suitable for 2.9 million load cycles. The high-pressure compaction of solid waste is not accomplished by impact in the process under consideration (pp. 147, 148, 153).

9. Press frame considerations suggest that the bale dimension parallel to the direction of the final pressure application be as long as possible within reasonable limits. Additional research on the transmission of forces through the bale in the compaction chamber might give guidelines leading to significant process improvements (pp. 150-152). [It might show, for example, that the bale dimension parallel to the direction of the final pressure application should be as short as possible in order to obtain a more uniformly compacted bale.]

10. The analyses of press frame design considerations include relatively new lightweight

frame construction principles. Some of these principles have been used successfully in Europe as well as at the IIT Research Institute in Chicago. They appear to be of advantage for the high-pressure compaction of solid waste, especially in multiple-axis compaction systems (pp. 148-153). [If the compaction press is simply designed so that the frame of the press supports or withstands the reaction forces resulting from the compaction operation, then it isn't important whether the force is applied to the horizontal or vertical plane; however, economics are achieved through minimization of foundation costs if presses are designed to compact in the horizontal plane.]

Compaction Equipment Performance Specifications:

1. The specifications discussed in this report deal with the functional performance required from the compaction equipment as a unit. They do not address themselves to equipment design needed to perform the task specified (p. 154).
2. The information given throughout this report indicates that several sets of such press performance specifications can and should be developed. The sets of specifications should be determined primarily by the materials to be compacted, press design and operation considerations, and local solid waste disposal conditions (pp. 135, 136, 152-154, 163).
3. Within the scope of this project, it was only feasible to develop one example of very general performance specifications for a solid waste compaction press. This example reflects the project findings as developed within given constraints which include the limitations of the press used in this project (p. 154).
4. Incorporating most of the major specification elements, this example is discussed in detail in this report. It provides for:
 - (a) the compaction of residential/commercial solid wastes in heterogeneous mixtures which behave like semi-elastics under compaction;
 - (b) a press capacity of about 250 tons per 6 hours (75 percent utilization during one 8-hour shift per day) or about 330 tons per full 8-hour shift;
 - (c) applied pressure of 2000 psi in the final compaction stage;
 - (d) a pressure hold of 15 seconds at 2000 psi;
 - (e) an overall volume reduction capability of 18:1;
 - (f) a total cycle time of 1 minute;
 - (g) a service life of 2.9 million cycles;

(h) a bale size in the compaction chamber of 25.7 by 27.7 by variable inches, on the average 34.0 inches, which was determined by selected rail-haul requirements (p. 154).

[This report does not provide evidence to indicate that this example of general performance specifications for a solid waste compaction press takes into account that a pressure loss occurs within the bale in the direction of the applied force. It is also not evident that it would be reasonable to expect that a stable bale of this size is possible at an applied pressure of 2000 psi in the final compaction stage.]

5. These press performance specifications as well as some of the key findings herein presented are confirmed by reports of solid waste compaction studies and equipment proposals submitted by European organizations after the completion of this project's research efforts.

Compaction Equipment Cost:

1. The compaction equipment cost data presented in this report include depreciation of the purchase price and power and maintenance. They do not include interest and other financing charges, return on investment, and personnel. The depreciation is calculated on a 20-year write-off period although the service life of similar presses has been found to be 10 to 15 years longer (pp. 155-160).
2. An analysis of prices and cost/performance parameters for existing hydraulic presses, which in case of need, are suitable for the high-pressure compaction of solid wastes, indicates that depreciation and power amount to about 50 cents per ton in 7-hour/5-day-per-week operations. An additional 7-hour shift would reduce these costs by about 15 to 25 cents per ton (p. 156 and Table 53).
3. However, none of the existing presses was specifically designed for the compaction of solid wastes; consequently, the cost data reflect the price of using "substitute" equipment. Thus, these analyses suggest that the high-pressure compaction of solid waste might cost, as reported in the APWA rail-haul interim report, less than 40 cents per ton including all major equipment investment and operating charges but excluding financing costs, labor, and return on investment (p. 156).
4. A higher press utilization factor than was used in this analysis could significantly improve this cost/performance ratio. Cost estimates made for a lightweight-frame solid waste compaction press indicate that the basic investment cost may be reduced substantially—perhaps by as much as 50 to 60 percent

excluding development expenditures. This would compound the advantages gained by increasing the utilization of the press (pp. 147, 156, 160). [Depending on the number of presses produced, the development expenditures when taken into consideration may drastically reduce these gains.]

Implications of High-Pressure Compaction System:

1. The implications of high-pressure compaction for the rail-haul of solid wastes are discussed to some extent in this report; however, there are plans to cover them in more detail in a separate publication being prepared on Rail Transport of Solid Wastes, by the APWA. This report presents only some of the preliminary findings that could be developed in connection with work performed during the compaction test program (pp. 135, 160-163).
2. Concerning transfer stations, the rail-haul link, and the ultimate disposal of the bales by the sanitary landfill method, the information shows:
 - (a) that high-pressure compaction of solid waste is highly applicable to rail-haul; and, most important,
 - (b) that the combination of high-pressure compaction and rail-haul results in environmental control benefits comparable to those available in the currently acceptable methods of processing solid wastes (pp. 160-163).
3. High-pressure compaction of solid wastes could also increase the utilization of sanitary landfill space.

3. CONCLUSIONS

1. The application of high-pressure compaction to solid waste disposal has been examined experimentally and theoretically in quite some detail and appears to be a process which can be applied on a production scale with many attendant advantages.
2. It has been demonstrated that stable bales can be produced by the high-pressure (2000 to 3500 psi applied pressure) compaction of loose and sacked household refuse; and that these bales can successfully survive the handling and shocks associated with comparatively long (up to 700 miles) rail-haul trips.
3. The results indicate that further investigation is needed and warranted for the development of process and equipment improvements and to establish the technical and economic feasibility of this basic process as a component of a total solid waste management system.

4. COMMENTS

This report presents the results of the first phase of a project which had as an ultimate objective, the development of "the optimum requirements for the design of suitable production-scale (compression) equipment." Further work is required to achieve this ultimate goal. For example, the project does not completely answer questions on the impact of moisture content on bale stability, public health, and environmental control. Although the work reported represents exploratory research and a number of the results are, therefore, indicative rather than definitive, many relevant considerations and observations are documented. To guide the reader and to encourage him to scrutinize the entire report rather than just this initial chapter, we have summarized each chapter and pointed up those features to be considered in reading the text.

One of the general organizational features of this report is that because of the large amount of information presented, considerable cross-referencing might be required by the reader depending upon his objectives.

It is important to note that the material on compaction is organized according to results on:

1. Residential refuse—loose (pp. 43-57);
2. Residential refuse—paper-sacked (pp. 57-59);
3. Residential refuse—shredded (pp. 59-63);
4. Synthetic refuse—loose (pp. 64-67);
5. Synthetic refuse—paper-sacked (pp. 67-69);
6. Synthetic refuse—paper and water (pp. 69-72);
7. Synthetic refuse—papers and adhesives (p. 72).

If one is interested, for example, in the effects of holding times of applied pressure, there are discussions and summaries of the data on the effects of holding times on residential waste, paper-sacked waste, and height of bales in the appropriate sections on pages 46-49, 57, 59-62, 64 and 66-69. Similarly, the effects of moisture with respect to the type of wastes used are given on pages 33-41, 56-57, 59-62, 64 and 69-72. The reader must keep track of the heading under which a particular result is discussed. Also, the reader must refer to the text proper for qualifying statements that are not always apparent from a particular table or chart.

The authors of Chapter III have chosen to report their results in summary form rather than present the basic data for each individual experiment. Where several samples have been subjected to the same treatment, the distribution of results is reported only in terms of the maximum, minimum, and average values. Although this presents adequate information

for many readers of the report, results of each individual test would have been more useful to the researcher. It is to be noted that a large number of results are obtained from annotated recording equipment charts which registered the actual applied pressure and the ram displacement of the high-pressure ram as functions of time. These recordings were not made available in the report for further evaluation. The reader should pay special attention to the fact that in several tables and charts the results of a single experiment under one set of conditions is compared to the average results from a large number of samples under another set of conditions. Chapter III concludes (pp. 76-85) with a number of pictures of the compaction process and compacted bales. The bales are classified by composition, pressure applied, and time of pressure application. However, information has not been provided to indicate the acceptance

of the bales in terms of stability or appearance. In the application of the results of the compaction experiments to the rail-haul study, the important properties are the final volume of the compacted bale after springback and the stability of the bale rather than the in-press volume reduction ratio.

The reader should take special note that most of the compaction experiments described in Chapter III were made with bale sizes which ranged in the compaction chambers from 14 to 18 inches high, that an extrapolation is made in Chapter V to a bale size of 34 inches high to obtain optimum loading of rail cars. It should also be noted that the configuration of the press influences the findings to some unknown degree and that no experiments were conducted on the larger size bale. Therefore, further research is needed to establish the stability of bales of the size recommended for optimum loading.

CHAPTER II

THE BASIC FRAMEWORK OF THE PROJECT

Chapter II identifies the basic framework of this project in terms of project background, project objectives, and project execution.

SECTION ONE—PROJECT BACKGROUND

This project was initiated at the end of November 1967, as a result of findings developed previously by the Research Foundation of the American Public Works Association in a study on the rail-haul of solid wastes. The APWA study is carried out for the U. S. Department of Health, Education, and Welfare and many local government jurisdictions in both the United States and Canada. The rail-haul study findings suggested:

1. that the high pressure compaction and/or baling of solid wastes is the most effective and economical way of processing solid wastes for large quantity shipments through rail-haul to remote disposal areas,
2. that solid waste compaction is consequently one of the most vital rail-haul system development inputs, particularly for operations designed to service large metropolitan areas,
3. that a full-or semi-production-scale solid waste compaction test program would supply the answer to a critical need and speed up the implementation of solid-waste rail-haul systems, and
4. that the results of a solid waste compaction test program, as envisioned, would benefit not only rail-haul system developments, but, in addition, other facets of solid waste disposal as well.

The above findings were derived from preliminary experiments conducted by the APWA rail-haul study team in order to ascertain the feasibility of high pressure compaction for solid wastes. The information gathered by spot tests and some of the conclusions drawn are detailed in an interim report entitled, "Rail Transport of Solid Wastes—A Feasibility Study," October 1968. This report has been published by the U. S. Department of Health, Education, and Welfare, Public Health Service, Consumer Protection and Environmental Health Service and Environmental Control Administration.

In summary, the spot tests showed conclusively that the high pressure compaction of solid wastes is feasible. However, they also showed that additional testing was needed (a) to substantiate the preliminary

test results, (b) to investigate more thoroughly the many factors of significance in the high pressure compaction of solid wastes, and (c) to determine the operational implications of this new and promising approach to solid waste processing. It was apparent that more supporting information was needed for both government and industry to convert promising indications into practical technology.

The formal proposal for the compaction project was filed on January 14, 1968. The project was approved on March 1, 1968, and funded for a May 1, 1968, starting date. The actual testing began on January 28, 1969. The interim period was used to locate and acquire a used press, to recondition as well as adapt as far as possible that press for the test purposes, and to erect and equip the test facility needed.

SECTION TWO—PROJECT OBJECTIVES

Broadly stated, it was the basic objective of this research project to obtain production-scale information on the various parameters which affect the high pressure compaction of solid wastes into bales that would be readily handleable for rail-haul.

To accomplish this basic objective it was necessary to pursue a large number of corollary subobjectives. Within the constraints of effort and time, the subobjectives required the study team to investigate many aspects of the high pressure compaction of solid wastes such as:

1. the influence of selected pressure variables on compaction and baling,
2. the number and positioning of compression strokes needed to produce a suitable bale,
3. the effects of variations in the total cycle time as well as the speed of compression,
4. the advantages and disadvantages of various bale sizes and configurations,
5. the stability of the bales produced,
6. the implications of varying refuse compositions with respect to high pressure compaction and baling,
7. the necessary public health and environmental control requirements,
8. the techno-economic parameters of production-scale operations, and
9. the development of compaction equipment performance criteria to guide and enlist the research capabilities of industry for the benefit of

rail-haul systems, as well as the solid waste disposal field.

In the over-all, the project objectives were cast in terms of applied research and thus describe the project as both exploratory and developmental in character.

SECTION THREE—GUIDELINES UNDERLYING THE PROJECT EXECUTION

The project had to be executed within the framework of several conflicting demands. To be considered on the one hand were the comprehensive objectives of the project, the complexity and scope of the problem, and the stakes ultimately involved. On the other hand, there were tight constraints of manpower, time, and funds.

Thus, in contrast to most research projects, this project had only a minute margin for the always necessary exploratory and research development efforts. Hence it was crucial that stringently limiting guidelines be developed for both the setup and the execution of all the test and development activities.

I. THE FRAMEWORK FOR THE BASIC STUDY APPROACH

The framework for the basic study approach was characterized by significant experimental constraints and, since the press was out of order for one week, there was an actual testing time of only nine weeks. In addition, it was necessary to balance the manifold project objectives in terms of the professional efforts available for research.

Consequently, the study approach was structured to focus primarily on three key project goals even to the exclusion of other very worthwhile study subjects. The three goals selected concern:

1. the development of compaction equipment performance specifications,
2. the development of stable bales suitable for rail-haul, and
3. the exploration of possibilities for the development of a minimum-cost solid waste compaction process.

It must be highlighted in this context that, being both exploratory and developmental in character, this project was to take the first major step toward the application of a promising solid waste disposal technology. As a result, the basic study approach for this project had to be comprehensive in scope but selective in depth. Furthermore, in producing an initial version of a new technology, the approach had to be cognizant of further research which could be aimed at an evolutionary perfection of the basic process.

Finally, corresponding to the framework for the

basic study approach, the guidelines had to be relevant to real-life operational requirements. Specifically, considerations had to be given to:

1. the establishment of process performance parameters for high pressure compaction in terms of solid waste-rail-haul, and
2. the selection of the basic type of high pressure compaction equipment suitable, or at least acceptable, for the purposes of this research project.

II. PROCESS PERFORMANCE PARAMETERS OF HIGH PRESSURE COMPACTION IN TERMS OF SOLID-WASTE RAIL-HAUL

The main purpose of processing solid wastes for rail-haul is the improvement in the cost/performance relationship of the over-all system operations. Since solid-waste rail-haul involves primarily material handling and transport, the processing relates to the way the materials are made ready for transport and handling throughout the system.

As a result, the rail-haul-oriented performance requirements of high pressure compaction must be determined in terms of material input, throughput, process output, public health and environmental control implications, and cost.

1. Process Performance Requirements In Terms of Material Input

A solid-waste rail-haul system is intended to handle successfully and economically as great a variety as possible of the solid waste materials generated by residents, municipal operations, commerce, and industry.

These input materials may be characterized as heterogeneous material mixtures of sometimes widely varying compositions which, as a rule, behave like semi-solids under compaction. Specifically, urban solid waste mixtures might include items such as food scraps, nylons, textiles, facial tissues, newspapers, bound and unbound moisture, furniture, glass, refrigerators and industrial/commercial packaging materials.

In view of both the great variety and the possible combinations of input materials and the critically short project period, it obviously was not feasible to consider an all-inclusive test effort. Fortunately, however, residential wastes are reported to represent about 50 percent of the total urban solid waste load. Furthermore, they are also reported to contain many, if not most, of the kinds of solid waste materials discarded by industry and commerce.

Thus, it was decided to use in the compaction tests mainly residential solid waste mixtures and components, including oversized wastes.

2. Process Performance Requirements In Terms of Material Throughput

Transfer stations are needed in virtually all solid-waste rail-haul systems. They represent the first building block of the operations and the place where the compaction process would most likely occur.

To satisfy the demands for various types of transfer stations, the APWA solid-waste-rail-haul project is projecting the development of stations capable of handling 50, 100, 250, 500, 1,000, or 2,000 tons of solid waste per 8-hour shift. To put these ratings in perspective, it might be stated that a 50-ton transfer station appears suitable for servicing about 15,000 people, while a 2,000-ton station can service 500,000 to 600,000 people.

In converting these over-all throughput ratings of transfer stations into time-related process workloads, it must, of course, be recognized that an 8-hour shift does not always imply 480 minutes of actual working time. Depending upon the degree of automation, the process might, for example, be shut down for 60 minutes during each shift in order to allow for lunch and coffee breaks. Furthermore, it is not reasonable to assume that a station will always operate at peak efficiency. The implications of variations in the actual working time as well as the productivity of the compaction press are summarized in Table I.

The calculations include time variations from 35

to 100 percent in the utilization of the press, in order to gauge simultaneously the impact of peak loading that may result from existing schedules for refuse collection and delivery.

In analyzing these data it must be recognized that only a few communities need, at present, transfer stations capable of handling 1,000 or 2,000 tons of solid waste materials per 8-hour shift. In addition, the high cost of collection tends to favor the selection of multiple transfer stations with a smaller capacity, even in communities or regions that generate a large amount of solid waste materials. In the light of these arguments and the constraints of the project it was decided to focus the available efforts on press-throughput ratings below 2 tons per minute.

The implications of this decision are illustrated in Figure 1. In this figure the transfer station capacity ratings are plotted against production time as well as press throughput expressed in tons per minute.

The placement of the curves suggests that, within the constraints given in Table I, a 1,000-ton/8-hour shift transfer station should be served by two press units capable of handling 500 tons per 8-hour shift.

The curves furthermore suggest that, given an actual working time of only 6 hours per shift, a maximum press throughput of about 1.4 tons per minute would be quite acceptable for the same time conditions. A minimum throughput of 0.14 tons per

TABLE I
Conversion of Transfer-Station Throughput into Compaction-Process
Throughput, Expressed in Tons per Minute and Assuming Variations
in the Actual Working Time as Well as Selected Levels of
Productivity and/or Press Utilization

Transfer Station Throughput Requirement	Compaction Press Throughput							
	Actual Working Time Per 8-Hour Shift							
	480 Minutes				420 Minutes			
	Levels of Press Utilization				Levels of Press Utilization			
	100%/ 480 Min.	85%/ 408 Min.	50%/ 240 Min.	35%/ 168 Min.	100%/ 420 Min.	85%/ 357 Min.	50%/ 210 Min.	35%/ 147 Min.
(Tons/8-hr shift)	(all data expressed in tons per minute*)							
50	0.10	0.12	0.20	0.29	0.11	0.14	0.24	0.34
100	0.20	0.24	0.41	0.59	0.24	0.28	0.47	0.68
250	0.52	0.61	1.04	1.48	0.59	0.70	1.19	1.70
500	1.04	1.22	2.08	2.97	1.19	1.40	2.38	3.40
1000	2.08	2.45	4.16	5.95	2.38	2.80	4.76	6.80
2000	4.16	4.90	8.33	11.90	4.76	5.60	9.52	13.60

*Data are slightly rounded.

minute is indicated.

As a result of these considerations, process throughputs varying from 0.14 to 1.4 tons per minute were chosen as the prime concern for this research program. Thus, the compaction equipment is presumed to operate at an efficiency rate of 75 percent of the stated capacity.

3. Process Performance Requirements In Terms of Material Output

The output of the high pressure solid waste compaction process must be viewed in terms of form or shape of the materials, the size and stability of the individual output units, as well as material density.

a) Material Density

For the shipment of goods and materials it is important to consider both their volume and their weight. Both the space occupied and the weight to be carried represent, to varying degrees, cost factors.

The interrelationship between volume and weight is termed material density. A decrease in the volume of a given amount of material, while keeping its weight constant, increases the material density.

Analyses conducted during the APWA

solid-waste-rail-haul study suggest that the density of the materials shipped has a direct bearing on shipping cost. Factors such as car deadweight per ton of net load, utilization of the available freight carrying capacity, and train configuration represent some of the major variables. In certain instances, for example, a doubling of the material density might even reduce by one-half the number of a given type of cars needed.

In gauging material density targets for rail-haul operations, it was found prudent to base the decisions initially on the carrying capabilities of the standard types of rail freight cars presently produced. Custom-made designs, including high cube cars, are very expensive, as may be expected; they may cost two to three times as much as a standard car of equivalent capacity.

A comparison of the straight purchase price of rail cars, excluding any financing cost and return on investment, suggests already in itself that the desired density targets should be based on the utilization of the 100-ton car. The purchase prices are roughly as given in Table 2.

In evaluating the data in Table 2 it must be

TABLE 2
Range of Purchase Prices for Standard Rail Freight Cars
by Load Carrying Capacity

Type and Length of Car	Load Carrying Capacity	
	70 tons (dollars)*	100 tons (dollars)*
Box Cars		
40.6 feet	11,500 - 14,200	12,500 - 15,200
50.6	13,800 - 15,000	14,800 - 16,000
60.9	19,000 - 20,700	20,000 - 22,200
Gondola Cars		
Low side 3'6"		
52.6 feet	13,200 - 14,200	14,200 - 15,700
65.6	15,700 - 17,300	16,700 - 18,800
Flat Cars		
50 feet	11,000	12,000
60	15,000	16,500
68	17,250	18,250
89	20,600	21,600

Sources: Various railroads and railcar manufacturers.

*The Low values of the purchase price range reflect volume discounts which are attainable through orders involving several hundred cars.

recognized that 40-foot-long gondola and flat cars, as well as cars with load limits of 50 tons, are no longer considered production-line items. The data show that the purchase price, as a rule, increases by only \$1,000 with an increase in the load carrying capacity from 70 to 100 tons.

Concerning the 100-ton cars, the data in Table 2 also reveal an interesting relationship between purchase price and length of car. This relationship shown in Figure 2 on the following page suggests, for example, that an increase of 20 percent in the length of a 50-foot box or flat car increases the purchase price by approximately 40 percent. Thus, from a car investment point of view, it is evident that compact cars be given careful consideration in the selection of desirable material density targets.

For the purposes of this project, the data and

arguments presented thus far appear to be sufficient to indicate desirable density ranges of solid waste materials for rail shipment. The full case for the selection of a given rail freight car is planned to be made in the final report on the first phase of the APWA rail-haul project. Obviously, many cost factors in addition to the purchase price are involved.

The material density alternatives available within the framework of the above data are calculated by distributing the net load over the volume of car space. These calculations take the existing car-loading requirements and experience into consideration. For example, loading regulations require that flat cars, as a rule, be loaded only to a height of approximately 8 feet, if packaged materials of a kind similar to solid wastes are shipped. Furthermore, experience in the utilization of box-car space dictates that the

FIGURE 1
Compaction Rates for Various Levels of Productivity

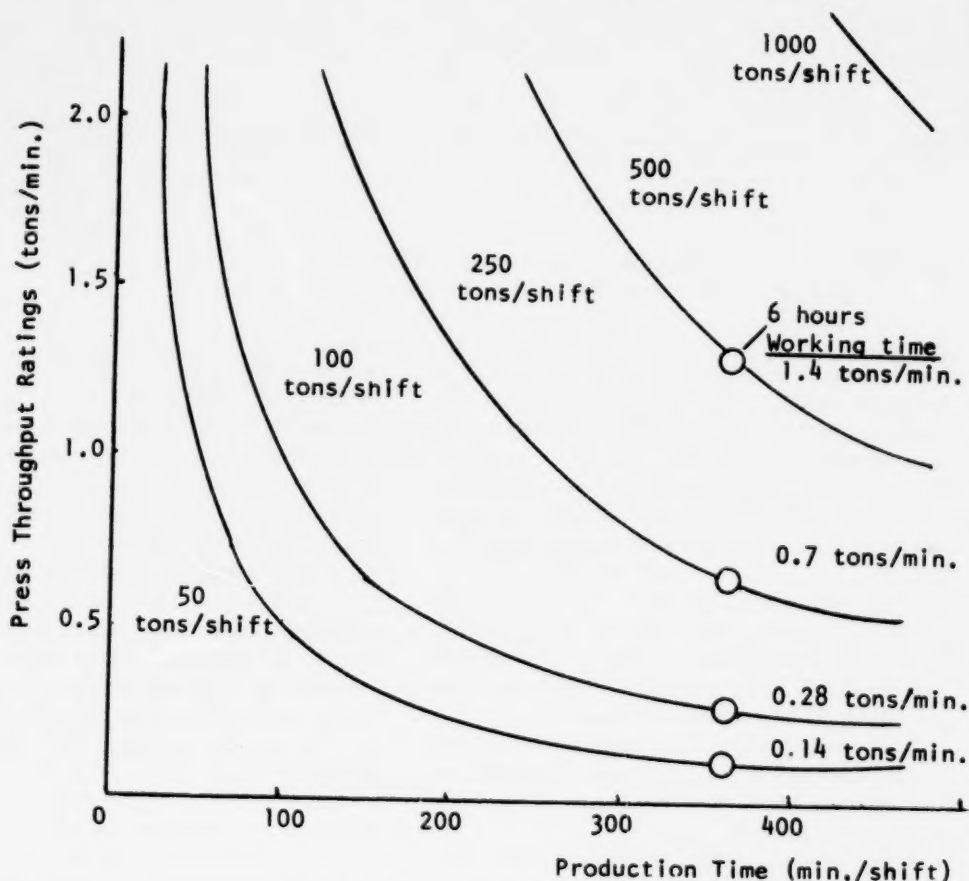
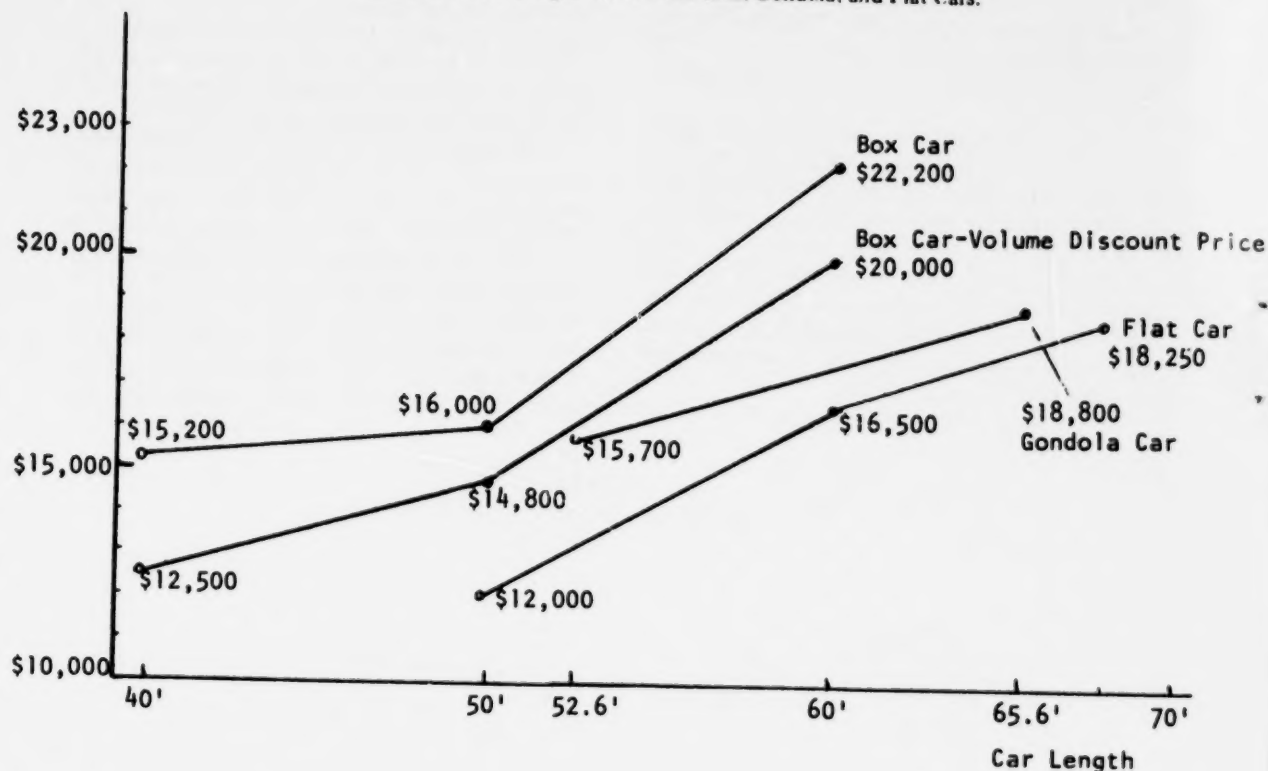


FIGURE 2
Correlation Between Increase in Car Purchase Cost and
Increase in Car Length for 100-ton Box, Gondola, and Flat Cars.



Source: Basic data on freight car purchase prices obtained from various railroads and rail car manufacturers.

theoretically available volume must be reduced by approximately 20 percent in order to arrive at realistic volume/weight relationships. Thus, the calculated density ranges for the materials to be shipped are shown in Table 3.

In interpreting the foregoing data it should be understood that the densities indicated represent minimum densities. These are the densities required if the net load capacity and the realistically available space are both to be fully utilized. A decrease in the density will result in a full utilization of the available space but an under-utilization of the net-load-carrying capacity. An increase in the density will result in an under-utilization of the available space.

As a result of the analyses presented in this part of the report it was decided to aim, if possible, for solid-waste-shipment densities averaging at least 50 pounds per cubic foot.

This decision carries significant implications concerning the application of pressure in terms of volume reduction and volume expansion after

compaction. Very high pressures, for example, are not to be investigated for their own sake within the scope of this project, i.e., if they do not cause an appreciable increase in the density above 50 pounds per cubic foot. Conversely, very low pressures are also to be de-emphasized if they fail to attain the volume reduction needed and potentially achievable on the basis of the materials being compressed.

b) Form and Shape of the Output

To provide maximum flexibility for solid-waste-rail-haul operations, it is necessary to consider the application of high pressure to the waste materials not only with respect to volume reduction but also with respect to the output form and/or shape of the product resulting from the compaction process.

Man has packaged goods and materials throughout recorded history to improve the productivity of his material handling efforts. Today only relatively homogeneous materials are, as a rule, shipped "loose" because they permit, by their very

homogeneity and if shipped regularly in sufficient quantities, the utilization of tailor-made and therefore most efficient material handling methods. Examples of such materials include grain, cement, and coal. But even coal is already processed to at least some degree in order to provide a relatively uniform unit size for the material handling functions involved.

Thus, if compaction is done at all, then it should also be used as far as possible to process the highly heterogeneous materials into a desired form. Consequently, the compaction of solid wastes might be considered as a method of packaging or "containerization". In keeping with current industry experience, compaction should furthermore aim to produce a "one-way" containerization. In the ideal case, the materials to be shipped should provide, by being processed through compaction, their own container or packaging.

The specific output form or "packaging" of the materials must, of course, be determined in terms of both the utilization of space in storage, transport, and landfill as well as the placement and stacking requirements of these operations. It is known that

specific configurations, such as spheres or hexagonals, add strength to a package because of their configuration. Nevertheless, industrial practice suggests that square or rectangular forms are preferred. These configurations are more adaptable to varying handling and storage conditions, particularly if packages of varying sizes might also be involved.

On the basis of these considerations it was decided to give, within the scope of this project, priority to the development of square or rectangular bales. Correspondingly, other configurations were only to be investigated if stability requirements and their implementation would suggest such a course of action.

c) Size of the Bales

Concerning solid-waste rail-haul, the size of the bale is primarily determined by the loading dimensions of freight rail cars. All the other material handling and transport operations could be adjusted readily to fit the size of the bale.

The loading dimensions of rail cars can vary considerably in the length and height of the car, but they are almost always fixed with respect to the

TABLE 3

Approximate Material Density Alternatives Given by the
Dimensions of Selected 100-Ton Standard Rail-Freight Cars*

Type and Length of Car	Theoretical Cubic Capacity	Practical Cubic Capacity	Density per Cubic Foot of Practical Cubic Capacity
<u>Box Cars</u>			
40.6 feet	4000	3200	62.5
50.6	5000	4000	50.0
60.9	6000	4800	42.0
<u>Gondola Cars</u> (Low side)			
52.6 feet	1780	1780	112.0
65.6	2220	2220	90.0
<u>Flat Cars</u>			
50.0	4700	3760	53.0
60.0	5640	4500	44.0
68.0	6390	5100	39.0

Source: Basic data on freight car purchase cost and dimensions obtained from various railroads and rail car manufacturers.

*All data are slightly rounded.

width of the car. Specifically, the limits of the loading dimensions of standard freight rail cars are approximately 9 feet wide, by a maximum height of 8 to 10 feet, by a maximum length of 60 to 70 feet.

These standard car dimensions make it necessary to size the solid waste bales primarily with respect to the width and, subsequently, the height of the car. The length of the car, although an important factor in car cost, may, for practical purposes, be considered in this context as a variable factor.

To achieve a maximum utilization of the potentially available freight car space, the shipping configuration of the bales should follow any one of the combinations of dimensions given in Table 4.

The table indicates that a wide variety of bale sizes are well suited to solid-waste rail-haul. For example, a bale could be dimensioned 9.0 x 8.0 x variable, or 9.0 x 4.0 x variable, or 3.0 x 8.0 x variable, or 3.0 x 4.0 x variable, etc. The data indicate, however, that at least one dimension of the bale should approximate 9.0, 4.5, 3.0, 2.25, 1.5, 1.12, or 1.0 feet.

In view of these considerations it becomes highly important to determine the springback characteristics of the compacted solid waste mixtures which, as a rule, contain elastic material components. Springback, as reported in the interim report on the APWA rail-haul study, was found to be an important factor in the high pressure compaction of residential solid wastes.

Considering, in particular, the need for at least one stable dimension of the bale, it is critical to determine not only the over-all springback volume and time, but, specifically, the dimensions of any directional orientation of the springback if such pattern exists. The directional patterns of the

springback determine primarily, of course, the dimensions of the compression chamber and the loading configurations of the bales for solid-waste rail-haul.

As a result of these deliberations it was decided to ascertain very carefully any directional orientation of the springback and to prepare the equipment specifications in terms of the bale dimensions indicated in Table 4 and the previous discussions.

d) Stability of the Bales

The requirements of a specific bale form and size necessitate that the bales be stable. Without stability there would be no control of form or size. Thus, the bale must hold together for a given period of time and be suitable for transport and material handling during that period of time.

In terms of time, solid-waste rail-haul is contemplated currently to include once-a-week pickup schedules for certain system configurations. Thus, a bale could be 7 days old before the beginning of the shipment and, assuming a 2-day rail transit, it could be 9 days old before placement in a landfill.

In terms of transport, the current rail-haul system developments include shipment distances of up to 150 miles. Consequently, bales 9 days old should be suitable for rail transport of that distance and, of course, be capable of withstanding the system associated material handling operations as well.

In analyzing the stability requirements it must, however, be recognized that bale stability can be produced by various means. For example, it might be achieved by the application of pressure alone, by the addition of adhesives before or during the baling operation, and by encapsulation and/or strapping after the bale exits from the press.

After evaluating these alternatives it was decided

TABLE 4
Approximate Patterns for Various Bale Sizes, as Suggested
by Rail-Freight Car Loading Constraints

Bale Dimension Alternatives in Terms of a Standard Rail Car		
Width	Height	Length
(feet)	(feet)	(feet)
9.00	Maximum or Variable	Variable
4.50	8.0	"
3.00	4.0	"
2.25	2.0	"
1.50	1.0	"
1.12	"	"
1.00	"	"

to emphasize first, of course, the production of bale stability by the application of pressure alone, and to investigate other alternatives only in case of need. Thus, within reason, the investigation of pressures higher than those needed for mere volume reduction becomes an important project objective.

Finally, since the application of various stability aids presupposes different conditions of the virgin bale, it was decided to ascertain the bale stability by a variety of methods ranging from visual observation to vibration and impact tests. Specifically, it was decided to develop a simple and fast stability evaluation method suitable for production-line operations by relatively untrained people.

4. Process Performance Requirements in Terms of Public Health and Environmental Control

Any development of new technology dealing with the disposal of solid wastes must, of necessity, consider the public health and environmental control hazards that might arise. Specifically, it must be ascertained whether or not the process by itself introduces a type and degree of pollution which is more severe than that caused by currently acceptable solid waste disposal operations. In terms of rail-haul, pollution might be introduced or reduced by the results of processing at the transfer station, during transit, and at the disposal site.

It must be recognized, of course, that almost all solid waste mixtures contain pollutants regardless of whether the materials are processed or not. Thus, pollution control research becomes critical in the development of new solid waste disposal technology only if (a) the process by itself causes a type or level of pollution which violates existing control standards and (b) cannot be dealt with in a suitable manner by already existing pollution control methods. If the process itself does not cause such a level or type of pollution, then the problem obviously does not exist.

To ensure the best allocation of the available effort, funds, and time it was decided, therefore, to undertake pollution control research only in case of apparent need. In the absence of such need, it was decided to rank pollution control through the compaction process among the benefits of the process or the highly desirable process refinements.

5 Process Performance Requirements In Terms of Cost

Waste, by definition, has no economic value. However, in economically developed, urbanized societies, waste not only lacks any economic value, it even has a negative economic value. In the United States, for example, solid waste disposal burdens the economy annually with \$4.5 billion of unreturnable,

though necessary expenditures in addition to the indirect costs resulting from the destruction or impairment of the environment.

In view of this situation, it is critical for the development of any new solid waste disposal technology to seek minimum cost approaches consistent with environmental control right from the beginning of the initial endeavors. Consequently, and considering particularly the constraints of this project, it was necessary to de-emphasize process improvements which might be desirable but which are not absolutely required for the establishment of a workable, acceptable, initial solid-waste-high-pressure compaction.

Correspondingly, it was decided to allocate as much effort as possible to the investigation of areas promising process economies exceeding those readily available at the present time. Specifically, it was decided to explore the feasibility of cost reduction in the equipment implementation, e.g., the press, through an initial conceptual investigation of alternative design approaches.

III. THE IMPLICATIONS OF THE PROCESS PERFORMANCE REQUIREMENTS FOR THE SELECTION OF THE RESEARCH PRESS

Limitations in time and funds eliminated the possibility of building a compaction device specifically designed for the purposes of this research project. As a result, it was necessary to make a judicious basic selection among the many types and sizes of secondhand equipment readily available. Simultaneously, it was necessary to consider carefully the possibilities and cost of making the necessary adaptations on the equipment that might be obtained.

1. The Selection of the Basic Type Of Compaction Equipment

Industry uses a wide variety of machines to force or form materials into desired shapes by the application of pressure. The pressures may be generated by hydraulic, pneumatic, or mechanical means of force development and force transmission. Furthermore, the pressures may be applied by pressing, hammering, or rolling.

Based upon the scope of the project and on both the type of materials to be compressed and the form of output desired, it was decided to use pressures applied by pressing. Rolling was excluded because it does not per se produce a bale or "package". Hammering was excluded because the maximum force is applied by short impact while the materials to be compacted, e.g., paper, may require a gradual application of pressure for maximum compaction

effects.

In terms of pressure force development and force transmission, it was decided to use a hydraulic press. Pneumatic presses are generally not built for pressure applications of about 2,500 psi, the pressure suggested by the exploratory research of the APWA rail-haul study team—and thus required for this compaction research project. Mechanical presses cover much of the same range in the maximum application of pressure as hydraulic presses. Also, they are, as a rule, faster than hydraulic presses, easier to maintain, and more efficient to operate because of the energy-storing flywheel.

However, within the constraints of a given single device, hydraulic equipment is more flexible and also more easily adjustable to meet varying requirements. Press requirements which were considered for this research project include: (a) the application of selected pressures below the maximum force, (b) the application of pressure increments at regulated intervals, (c) the holding time of a given pressure application, and (d) the application of pressure to specimens varying significantly in their ultimate size after compaction.

Finally, the selection of the press was made in consideration of the properties of the materials to be compacted. The characteristics of solid waste compositions require that the force be applied to the materials in an enclosed chamber. Considering the flow characteristics of semi-solids, e.g., mud, compression without an enclosed chamber would allow the materials to escape and an effective application of pressure could not take place.

Thus, for the purposes of this research project, it was decided to select a hydraulically operated press capable of applying upwards of 2,500 psi to solid-waste materials in an enclosed chamber. This selection, of course, does not imply that pneumatic or mechanical force development and transmission methods cannot be used alone or in combination with hydraulic methods in the high pressure compaction of solid wastes.

2. The Selection of the Compaction Equipment by Speed of Pressure Application

The available literature indicates that cycle times of 30 seconds are not uncommon for modern hydraulic presses operating in the pressure range required for this project. This implies that, theoretically, two bales of solid waste could be produced per minute.

Consequently, to fully explore the actual potential of compaction developments, the research press was required to be capable of applying the relevant compaction pressures within a time span of less than 30 seconds.

3. The Selection of Compaction Equipment by Size

The process performance requirements outlined above were used to identify parameters for the selection of the press in terms of size. In this context size refers to the dimensions of the compaction chamber and the volume reduction ratios incorporated in the over-all design of the press.

a) Dimensions of the Compaction Chamber

The dimensions of a suitable compaction chamber were derived by consideration of the interrelationship between over-all throughput ratings, the potential sizes of various bales, a set of density postulates, and the number of bales that ultimately might be made per minute. Thus, a set of progressive computations was required to identify a suitable compaction chamber size.

The over-all process throughput ratings or requirements, illustrated in Figure 1, can be converted to the corresponding weights per bales as shown in Table 5.

To obtain perspective, these weights calculated per bale must now be correlated to the potential sizes of the ultimate bale. Based upon the bale configuration in the form of a cube and the bale loading dimensions developed previously, the potential volume alternatives are given for the ultimate bale after springback in Tables 6 and 7.

The correlation between bale weight, Table 5, and bale volume, Table 6, is presented in terms of pounds per cubic foot in Table 7 on the following page. The data in Table 7 are then evaluated in terms of the densities estimated on the basis of the exploratory research conducted by the APWA rail-haul study team and reported in the rail-haul interim report. The density values, falling within the range of 60 to 130 pounds per cubic foot, are indicated in Table 7 by underlining.

The data developed in Table 7 can already be used to indicate desirable press-size benchmarks. Thus, in terms of guidelines underlying this project, the 4.5- and 1.0-foot bales are completely outside the scope of potential development goals. The densities correlating to these two bale sizes are found to be either too high or too low. Considering the four remaining potential bale sizes, the data dictate that, in case of need, priority be given to the 2.5- and 1.50-foot bale.

Finally, it must be stressed that the data in Table 7 refer to bales after springback. Consequently, a press still would be suitable if the dimensions of its compaction chamber were smaller. Assuming springback variations of 33, 50 and 100 percent, the corresponding volumes of the compaction chamber are shown in Table 8.

TABLE 5
The Weight of Solid Waste Bales in Terms of 360 Minutes
Effective Press Operations, Varying Overall Throughput
Requirements, and Variations in the Number of Bales
Produced Per Minute*

Overall Transfer Station Throughput Requirements	Corresponding Press Throughput Per 360 Minutes Actual Working Time	Weight per Bale	
		Per One Bale/ Minute	Per Two Bales/ Minute
(Tons /8-hr Shift)	(Tons per Minute)	(lbs)	(lbs)
500	1.40	2800	1400
250	0.70	1400	700
100	0.28	560	280
50	0.14	280	140

*Some data are slightly rounded.

TABLE 6
Bale Volumes Corresponding to Variations
in Selected Bale Dimensions Derived
from Rail Car Loading Dimensions

Side of Cube* (feet)	Volume of Bale (cubic feet)
4.50	91.12
3.00	27.00
2.25	11.39
1.50	3.37
1.12	1.40
1.00	1.00

* See Table 4

TABLE 7
Calculated Density Patterns Expressed in Pounds Per Cubic Foot
and Based Upon Variations in Bale Volume and Bale Weight as Suggested
By Solid Waste Rail Haul Operating Parameters

Side of Cube (Table 4) (feet)	Volume of Bale (Table 6) (cubic feet)	Alternatives of Total Weight of Solid Waste Bale* (Table 5)					
		2800 lbs. (lbs/cuft)	1400 lbs. (lbs/cuft)	700 lbs. (lbs/cuft)	560 lbs. (lbs/cuft)	280 lbs. (lbs/cuft)	140 lbs. (lbs/cuft)
4.50	91.12	30.72	15.36	7.68	6.14	3.07	1.53
3.00	27.00	<u>103.70**</u>	51.85	25.92	20.74	10.37	5.18
2.25	11.39	245.82	<u>122.91**</u>	<u>61.45**</u>	49.16	24.58	12.29
1.50	3.37	829.60	<u>414.80</u>	207.40	<u>65.92**</u>	<u>82.96**</u>	41.48
1.12	1.40	2000.00	1000.00	500.00	400.00	200.00	<u>100.00**</u>
1.00	1.00	2800.00	1400.00	700.00	560.00	280.00	140.00

* See Table 5 on Page 17

** Densities within the range of 60 to 130 pounds per cubic foot. Including oversized wastes such as refrigerators, bedsprings and furniture, the average potential densities have been estimated to range as high as from 60 to 170 pounds per cubic foot.

As a result of these data and deductions, it was concluded that a press would still be suitable for this research project if the volume of its compaction chambers were such as to allow for reasonable extrapolations of the test results to compaction chamber dimensions varying from 1.68 to 8.54 cubic feet. Ideally, it would, of course, be desirable if the dimensions of the research press compaction chamber would support extrapolations to cover the total range of the chamber sizes indicated in Table 8.

In evaluating the above compaction chamber size data, it must be recognized that they are based on the production of one or two bales per minute. This high speed of production allows the compaction chamber to be rather small but still suitable for the throughput requirements as dictated by the transfer station capacity ratings. Other operational press configurations are, of course, possible. A 1.4 ton throughput per 1 minute is, for example, the equivalent of a 4.2 ton throughput per 3 minutes, if the bale size is increased from 2,800 to 8,400 pounds per bale. However, even at a density of 100 pounds in the compaction chamber, the chamber would have to have a volume of 84 cubic feet or approximately 4 x 4 x 5 feet, which exceeds by far the dimensions of secondhand presses readily available. Thus the above calculations address themselves to the suitability of the secondhand presses available rather than to the dimensions of presses that might be built for the high pressure compaction of solid wastes.

b) Volume Reduction Potential

As is well known, solid wastes can be rather voluminous. Densities of loose household refuse are reported to vary from 100 to 270 pounds per cubic

yard or 3.7 to 10 pounds per cubic foot.

Thus, assuming an ultimate density after springback of about 50 pounds per cubic foot and assuming a minimum springback of about 33 percent, the density in the compaction chamber would amount to 75 pounds per cubic foot or about 2,000 pounds per cubic yard. In view of these data, it was decided to obtain a press in which the ratio between the volume of the charging box and the effective volume of the compaction chamber would be 15:1, or larger.

IV SUMMARY OF THE OPERATIONAL GUIDELINES UNDERLYING THE EXECUTION OF THIS PROJECT

On the basis of the information presented in Section Three of this chapter, it was possible to develop a simple operational code, or basic operational procedure, for this project. To put the necessity for this code into perspective, it must be recognized that the project deals with a subject which is not only very complex in itself, but also very susceptible to the inclusion of many additional research objectives and aspects.

The operational guidelines emerging from the findings, analyses, and evaluations indicated in Chapter II can be summarized as follows:

1. Confine the compression tests to residential solid waste mixtures and their components.
2. Base the process developments on material throughput or capacity ratings of 0.14 to 1.4 tons per minute.

TABLE 8
Compaction Chamber Bale Volumes Based on Various Amounts of Springback*

Volume of the Bale After Springback (Table 7) (cubic feet)	Compaction Chamber Volume Based upon a Springback of		
	33%	50%	100%
	(cubic feet)	(cubic feet)	(cubic feet)
27.00	20.25	18.00	13.50
11.39	<u>8.54</u>	7.59	5.68
3.37	2.52	2.25	<u>1.68</u>
1.40	1.05	0.93	0.70

*Data slightly rounded.

3. Try to achieve average material shipment densities of at least 50 pounds per cubic foot.
4. Avoid the investigation of very low or very high pressure applications, if they do not relate to the volume reduction or stability requirements of this project.
5. Give priority to the development of square or rectangular bales. Consider other configurations only in case of need.
6. Limit the developments to a maximum of four ultimate bale sizes—one of their sides being 1.12, 1.50, 2.25 or 3.00 feet. If necessary concentrate the research efforts on the 1.50-and 2.25-foot bale.
7. Determine carefully the amount and, in particular, any directional orientation of springback occurring in the bales after exit from the press.
8. Develop bales which are stable for 9 days and suitable for rail transport of up to 150 miles within this time period.
9. Emphasize the application of pressure for achieving bale stability. Investigate other stability aids only in case of need.
10. Check for pollution caused by the compaction process itself. Engage in pollution control research if compaction by itself causes any form of pollution which cannot be handled in an acceptable manner by existing control methods.
11. Orient all investigations toward the establishment of a compaction process of minimum cost. Investigate specifically avenues of possible equipment development which promise cost reductions and thereby will foster a more widespread application of the high pressure compaction process.
12. Obtain a hydraulic press which
 - a) is capable of applying relevant pressures upwards of 2,500 pounds per square inch within a time span of less than 30 seconds to solid waste materials in an enclosed chamber,
 - b) has dimensions of its compaction chamber which can support an extrapolation of the test results to compaction chamber dimensions ranging from a minimum of 1.68 to 8.54 cubic feet to a maximum of 0.70 to 20.25 cubic feet, and
 - c) provides an in-press volume reduction potential of at least 15:1.

These guidelines were applied constantly throughout the project to both the problems encountered and the findings as they developed. Thus these guidelines determined ultimately the scope as well as the depth of this project's total results.

Correspondingly, these guidelines must be kept in mind in evaluating the project findings. Although many of this project's efforts deal with physical science phenomena, they are conditioned by the experimental setup and constraints. Thus some of the results are, for example, peculiar to the press used or the process operations pre-supposed, while other results are independent of these constraints. The limitations of the project did not allow attempts to dimension the effects of such constraints by investigations specifically oriented toward this purpose. It is therefore recommended this research aspect be included in any follow-up project that might be contemplated.

CHAPTER III

THE HIGH PRESSURE COMPACTION OF SOLID WASTE MATERIALS

The main objective of this part of the study was to gather technical data necessary for the development of a suitable process which could be utilized both to decrease the volume of wastes and to produce cohesive refuse bales stable for rail-haul handling and transport.

In order to achieve the above objective, experiments were carried out to study the effects of waste compositions and compaction conditions on bale formation and the resulting bale properties.

The experimental setup and experimental techniques used or developed are described in Section One. Additional experimental information pertaining to sets of specific experiments is presented at appropriate places in the other chapters. Section Two contains a description of the wastes used in the study and Section Three presents the results of the compaction experiments as well as the interpretation of these results.

SECTION ONE—EXPERIMENTAL SETUP, PROCEDURE, AND MEASUREMENT DEVELOPMENT

This section describes the hydraulic press used for the compaction of wastes, the operation of the press, the electronic measuring system attached to the press, and the measuring procedure. It also presents the experimental setup and findings of three measuring methods investigated during this program and designed to study the development of forces during bale formation.

I. EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup used for the compaction of wastes consisted of a three-stroke hydraulic press and attached electronic measuring equipment.

1. Compaction Press

The press, donated to the project by General Motors Corporation, was a 17-year-old normal metal scrap baler which was reconditioned and modified. A sketch indicating the three-stroke arrangement of the press is given in Figure 3.

The original water-oil emulsion system was converted to an oil hydraulic system. In addition, the total force of the high pressure ram (third ram) was increased from 430 tons to 610 tons by the addition of two, 8-inch diameter booster cylinders. Another modification introduced into the press was the addition of a series of ram locks powered by a separate 2,000 pounds per square inch hydraulic system.

The ram lock system consisted of six, 6-inch diameter cylinders, one cylinder holding the rolling cover at the top of the press box in place, three cylinders holding the low pressure gathering ram (ram 1) in place, and two cylinders holding the intermediate ram (ram 2) in place. The locks were provided to prevent the movement of the first and second low pressure rams and the cover during the final high pressure compaction. This was found necessary because previous observations indicated that high expansion forces can be created during the compaction of refuse.

The opening and closing of the cover, and the return movement of the first and second ram was accomplished by the use of compressed air from a Worthington air compressor and a low-pressure air accumulator. Hydraulic power was supplied to the system by two double-end pumps. These pumps were capable of delivering 83 gpm of oil at 1,250 psi, and 55 gpm at 3,500 psi, respectively. The pressure of the second pump was limited to 2,500 psi by a Vickers relief valve. Each pump was driven by a 75 hp, 1,200 rpm electric motor connected to a multiple "V" belt drive. The return of the third ram was accomplished by gravity.

The gathering ram (Ram 1, Fig. 3) was mounted horizontally in the press. The dimensions of this ram were 60 x 42 inches in platen face area and 11 inches in ram diameter. It was calculated that the ram exerts a total force of 119 tons, or 94 psi, for a line pressure of 2,500 psi.

The intermediate ram (Ram 2, Fig. 3) was also located horizontally but at a 90 degree angle to the gathering ram. The area of the platen face of this ram was 42 x 16 inches and the diameter was 14 inches. The total force exerted by the intermediate ram was calculated to be 192.5 tons, or 573 psi for a line pressure of 2,500 psi.

The high pressure ram (Ram 3, Fig. 3) was originally powered by an 18-inch diameter single-acting cylinder which developed 430 tons. The addition of two 8-inch diameter single-acting booster cylinders increased the available force to 610 tons, or 3,769 psi, across the 16'x 20 inch platen face. However, a cutoff valve installed in the system reduced the utilized pressure to about 3,500 psi. The calculated unit pressure of this ram was equal to the line pressure times a factor of 1.11.

An Oilgear 3/8-inch relief valve, having a pressure

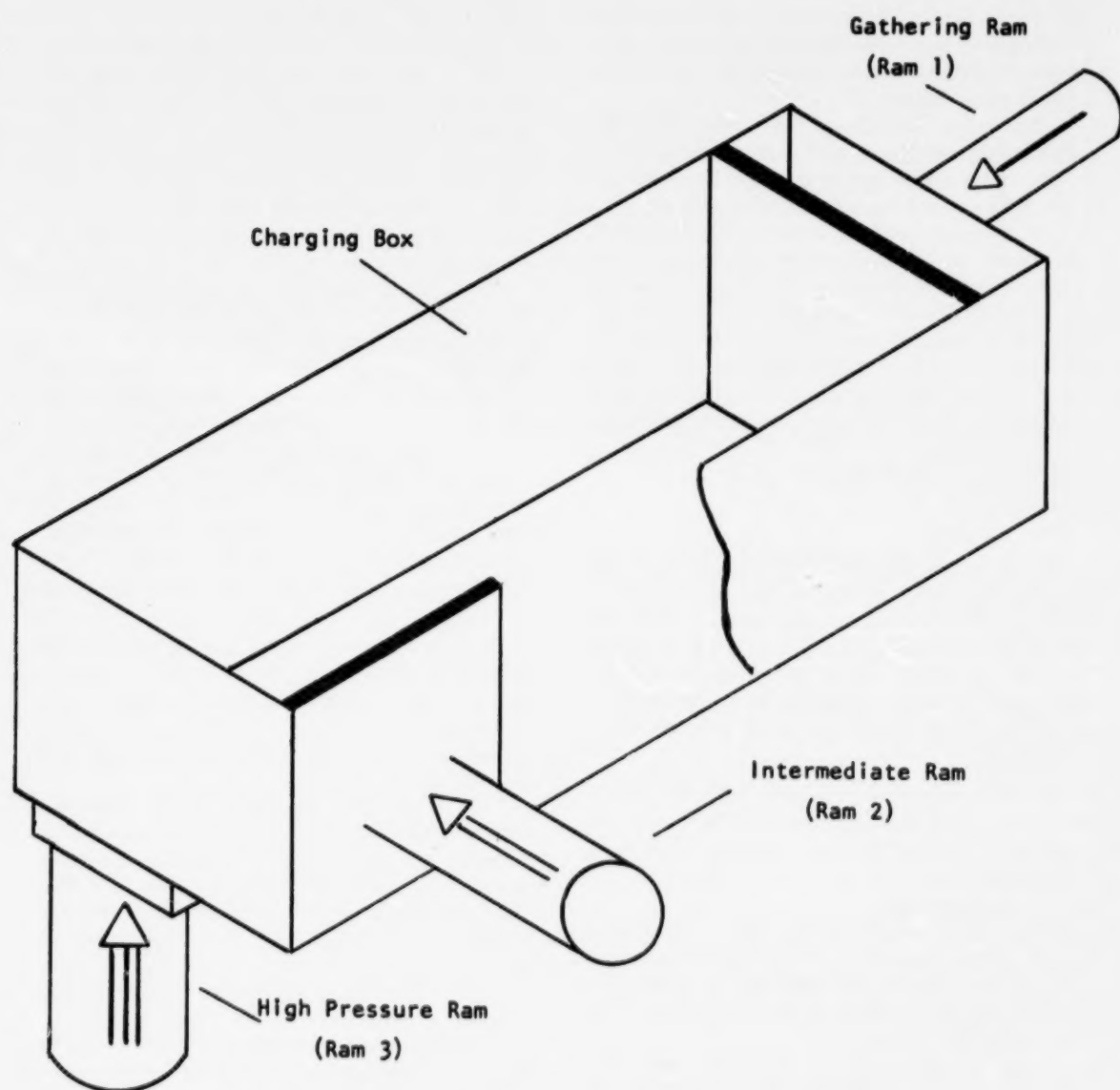


FIGURE 3
Compaction Press

range of 500 to 5,000 psi, was installed during the program to provide fine control of the system's oil pressure to the rams.

2. Press Operation

The press was operated manually. The press operator initiated all operations with the exception of the safety locks which were automatically actuated by limit switches.

The procedure of operating the press during compaction was as follows:

- a) All pumps were started and the air circuit was brought up to pressure.
- b) A premeasured charge of refuse was loaded into the open charging box.
- c) The charging box was closed by advancing the cover on top of it.
- d) The cover was locked into position.
- e) The gathering ram was then advanced and it too was locked into position.
- f) The same operation was again repeated with the intermediate ram, and after its locks were in position, the high pressure ram was ready for operation.
- g) The high pressure ram was then advanced until it reached a predetermined pressure, and the compaction was completed.
- h) To remove the bale from the press, all three rams were first moved slightly out of position to remove the pressure from the bale.
- i) After removal of the cover plate from the top of the box, the third ram was again activated to eject the finished bale out of the

charging box.

3. Measurements of Press Parameters

An electronic measuring system was installed to allow the measurement of several press functions:

- a) Ram displacement of the high pressure ram;
- b) Hydraulic pressure of the high pressure ram; and
- c) Ram displacement of the intermediate ram.

These functions were sensed with transducer elements that converted the input variables to electric signals. These signals were then amplified and used to drive recording styli to produce time-history records of the event. At a later stage of this work a second output device was added to produce a direct plot of the applied pressure versus the displacement of the third ram.

Functionally, all three signals were processed as shown in Figure 4.

The individual elements of the measuring system are described in the following paragraphs.

Block A: Pressure Transducer

The hydraulic pressure to the high-pressure ram was measured by a Transducer's Incorporated Gage, Model GP 56F-7500. This is an electrical gage assembly in which the applied pressure produces a force which loads a column. Electrical gages sense strains in the column as it deforms during the application of pressure. The strain gages were wired in a Wheatstone bridge configuration so that an output

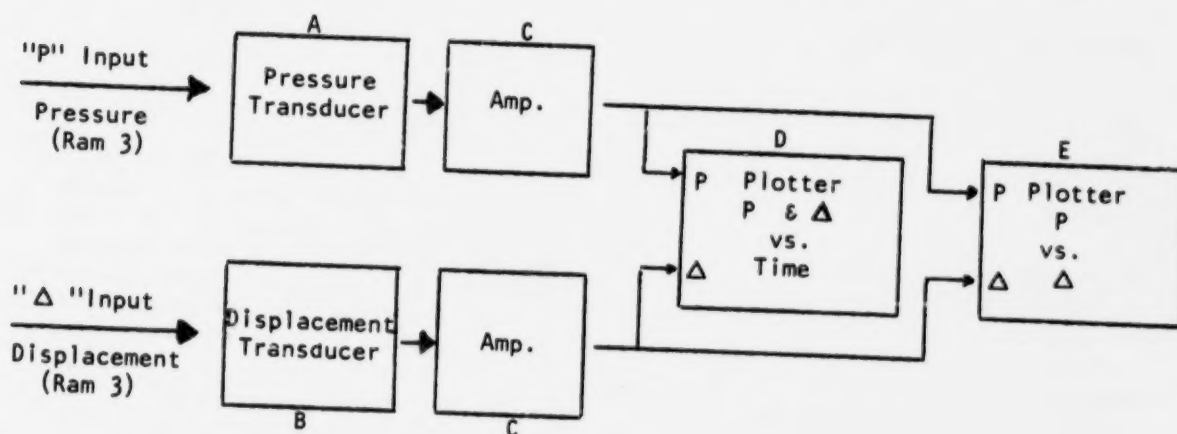


FIGURE 4
Electronic Measuring System Diagram

voltage develops from the bridge as pressure is applied.

Block B: Deflection Transducer

The two deflection or position transducers used in the setup were Model WR8 50A manufactured by the Lockheed Electronics Company. Basically, these gages are electrical potentiometers whose slider position is controlled by the extension of a measurement cable. Thus, if a voltage is impressed across the ends of the potentiometer resistance, the voltage measured between the slider and either end of the resistance will be an electrical analog of the position of the slider and/or the extension of the cable.

Block C: Signal Amplifying Equipment

Equipment used for the supply of power to the gages and to amplify the signals from the recorder was manufactured by Electronics Limited, Series 2800. The signal conditioning equipment contained all the necessary controls to power the gages, adjust their balance points, control the sensitivity of the measurements, and calibrate the pressure channel.

Block D: Two-Channel Plotter

The two-channel, time-base plotter used was the Model TR 722 manufactured by Technirite Electronics. It provided a chart record of two input signals versus time, at different paper speeds and signal sensitivities.

Block E: Two-Channel Plotter

This plotter was a Mosely 2D series instrument which recorded the pressure versus displacement on a graph. It utilized the same signal input as the TR 722 but contained its own controls of sensitivity and positioning.

4. Calibration of the Deflection and Pressure Measuring System

Each run of the press provided a check of the deflection calibration system of the high pressure ram, since the ram always started its travel from a zero position and, as the bale was ejected, reached its full extension. This known travel distance was used to set the sensitivity of the deflection channel.

Calibration of the pressure measuring channel was by signal substitution: the electrical signal whose pressure equivalent had been established could be

injected into the channel by operation of a push-button control. The equivalence to pressure was established at the test site by subjecting the pressure transducer to an accurately known pressure from a dead weight pressure gage calibrator.

II. DEVELOPMENT OF METHODS FOR THE MEASUREMENT OF FORCES AT THE BALE-PRESS INTERFACE AND WITHIN THE BALE

In addition to measurements of press parameters, as described in the previous section, an attempt was made during the study to measure the forces active in bale formation. This was done since a knowledge of the various forces developed in the press frame, at the bale interface, and within the bale are of importance both with respect to press design and for the understanding of the compaction process.

Furthermore, information of this type and applicable to the compaction of wastes is found to be nonexistent. To complicate matters, it was also found that standard measuring techniques and methods which can be used for the determination of these forces are not easily adaptable to refuse compaction and that new methods have to be developed or adapted.

Ideally, measurements should be taken of the magnitude of the forces, the various displacements and density distributions within the bale, and of the normal and shear forces at the bale and chamber interfaces.

Due to the limitation of time and manpower, the exploration and development of suitable techniques had to be limited. Nevertheless, an appreciable amount of work was done and several approaches were evaluated. One of these approaches showed great promise; it utilized penetration gages for measurements at the interfaces between the chamber walls and the refuse. The resultant force measurements obtained by this method are presented in Section Three.

Initially, it was necessary to establish the general mechanics of refuse bale formation to ascertain whether a particular approach merited further investigation. Since uncompressed refuse occupies an appreciably larger volume than compacted refuse, the mechanics of the process involves movement of the refuse during compaction. In a three-stroke press, as used in this study, the movement of the refuse into the final space is accomplished by the successive movement of each ram located at different angles. This results not only in a change of the initial position of the refuse, but also in successive changes in the position of the individual items in the refuse subjected to forces applied from different directions.

The above facts indicate the high probability of failure of any method which utilizes electrical leads and connections between the gaging elements placed inside the refuse and the outside of the compaction chamber. Thus it was decided to explore only those methods for measurements of forces within the bale which would be self-contained. This dictated the use of mechanical gages of the "peak reading" or "final reading" type.

The measurement of forces at the bale-chamber interface was attempted in two ways: one utilized electrically gaged liner plates in the compaction chamber, and the second used a mechanical gage assembly specifically constructed to cover the area of the high pressure ram face.

A description of the various methods tested and their evaluation is given in the next sections.

1. Measurements within the Bale

Pressures developed within the bale during compaction were measured with locally manufactured small penetrometer gages. Each gage occupied a volume of about 1/4 cubic inch. It was essentially a sandwich-type construction of two 1/2 inch square, 1/8 inch thick steel plates, with a hardened steel ball placed between them. A sketch of the gage assembly is shown in Figure 5. To hold the two plates parallel and avoid movement of the ball from its proper position, the gage assembly was held together by a soft wax and coating of tape.

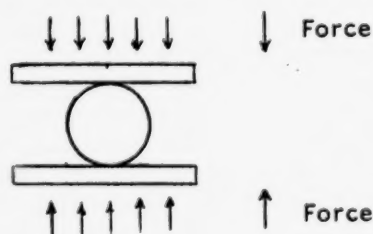


FIGURE 5
Penetrometer Gage

The application of forces normal to the two planes of the gage introduces high-contact stresses between the ball and plate. These stresses produce local deformations in the plates, resulting in circular depressions. The diameters of the depressions are related to the applied force. Although the relationship is not linear, reasonable linearity can be obtained in a given pressure range by proper selection of ball diameter and plate hardness.

One of the features inherent in this gage is its strength to normal forces and its weakness with

respect to applied shearing forces. In the presence of significant shear forces the gage is likely to separate into its individual elements. In the case in which the shear forces would be developed after initial normal forces were applied, the penetration marks were expected to be elliptical rather than circular.

Several tests were carried out to ascertain the applicability of these gages for internal force measurements in the bale. The gages were either randomly distributed in the loose refuse or were interconnected with Scotch tape and attached to specific refuse items. The refuse was compacted and the compacted bales were then dissected in order to retrieve the inserted gages, and to determine the location and orientation of the gage assembly within the bale.

Difficulties were experienced with respect to the retrieval of the gages inside the baled refuse, since their movement during compaction could not be predicted. Similarly, it was difficult to avoid displacement of the gages from their positions during retrieval. This impaired the determination of the exact orientation of the gages, with respect to the applied force in the bale, a requirement necessary for the evaluation of the measured force.

Of the 25 gages inserted into the refuse, two had sheared and separated into their elements. Five gages showed noticeable elongations of the indents. However, the track width did not vary significantly, indicating shearing and constant normal forces. The other gages showed clean indentations; however, the indentations were, in most cases, very slight.

Measurements taken from the gages indicated that the peak force was probably applied to the bale only during the final few inches of compaction. Thus, it seems valid to assume that in the majority of cases the measured peak force would represent the force applied to the gage at, or very near, its final orientation.

Although the results showed that the approach had promise, it was clear that the necessary refinements of the method would require more time than was available during the present study. It is recommended, however, that the investigation of this method be continued in a future study.

2. Measurement of Forces at the Press Chamber Walls

In order to measure the forces developed at the chamber walls of the press and their development with time, the liner plates of the chamber were equipped with strain gages. It was hoped to measure both normal and shear forces during bale formation on at least three faces of the press.

Limitations of strength within the press structure and the arrangement of the ram system of the press did not allow the insertion of a system occupying a larger volume than the available space within the liner plates. These plates were removable sections used to protect the heavy steel outer box which provided strength for bale formation. The thickness of the liner plates was only three-quarters of an inch.

Due to the limitations in thickness of the plates and the need to place all gaging and wiring on the backside for protection, a simple clamped diaphragm sensing element was selected as a measuring device. The sketch below (Fig. 6) shows the arrangement.

To form the diaphragm section and gage cavity, metal had to be removed from the liner plate. This, naturally, introduced a discontinuity in the liner plate wall stiffness which could affect the measurements. In addition, the bulk modulus of the waste materials was not known and as a result its effect on the measuring system could not be predicted. It was decided, therefore, to test one gaged liner plate outside the press.

The gaging of the liner plate was based on the following considerations:

a) Application of a distributed normal force produces tensile strains in the center lower surface of the reduced section of the liner plate. These forces are sensed by an attached electrical strain gage. If the forces are uniform and normal then the isostrain lines form concentric circles about the center.

b) Application of a shear force will distort these circles. Thus, it was reasoned that by a judicious location of a number of strain gages in the plate, a good measure of the normal force and a fair measure of the shearing force could be obtained.

c) It was calculated that for a safety factor of 2, at rated nominal working force, and a diameter-to-thickness ratio of 7.52, the diameter of the machined cavity in the 3/4-inch plate must be approximately seven and one-half times the thickness of the diaphragm. For a diaphragm thickness of 0.222

inches the minimum space requirement of gage location, wiring, etc., was found to be about 1-5/8 inches. Gaging elements conforming to these dimensions were installed in a plate.

The gaged plate was tested by application of known loads applied on a 4-inch diameter, circular loading platen in a standard testing machine. A variety of waste materials was placed between the loading platen and the gaged plate. These included paper sheets of various thicknesses placed either parallel or perpendicular to the gaged plate, rubbers of different thicknesses, lead, lead discs, and shredded paper. The results of the tests are plotted in Figure 7.

It can be seen that the plots of gage response versus transmitted load which were obtained for different materials were, in the majority of cases, appreciably different from the predicted response curve.

In addition, with the exception of the experiments carried out with paper sheets placed vertically to the gaged plate (8, 9, 10), the resultant measured load was found to be lower than the expected value.

Load values obtained from lead, rubber, and shredded paper were close to the predicted values. In each case in which paper sheets were placed horizontally to the gage plate, much lower values were recorded. Vertically placed paper simulated, in most cases, higher load values than actually applied but lower values were also obtained.

The large spread of the load versus response curves obtained for paper alone indicate the strong effect of its configuration with respect to the gage sensing element. Point loading most likely (vertically placed paper) led to steeper curves simulating in the upper pressure region a higher pressure than was actually applied. When paper sheets were placed horizontally the material apparently acted as a bridge across the more deformable sensing area. As a result, the diaphragm experienced a lesser load than applied, and the stiffer area—the solid plate adjacent to

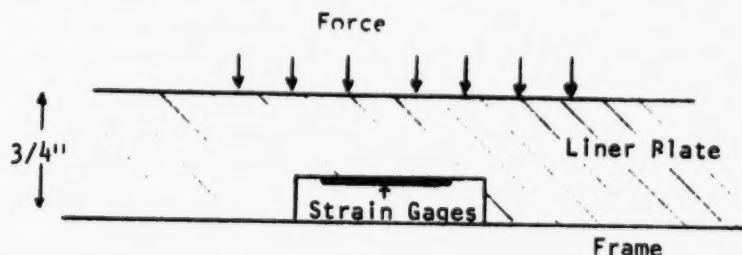


FIGURE 6
Strain Gaged Liner Plate

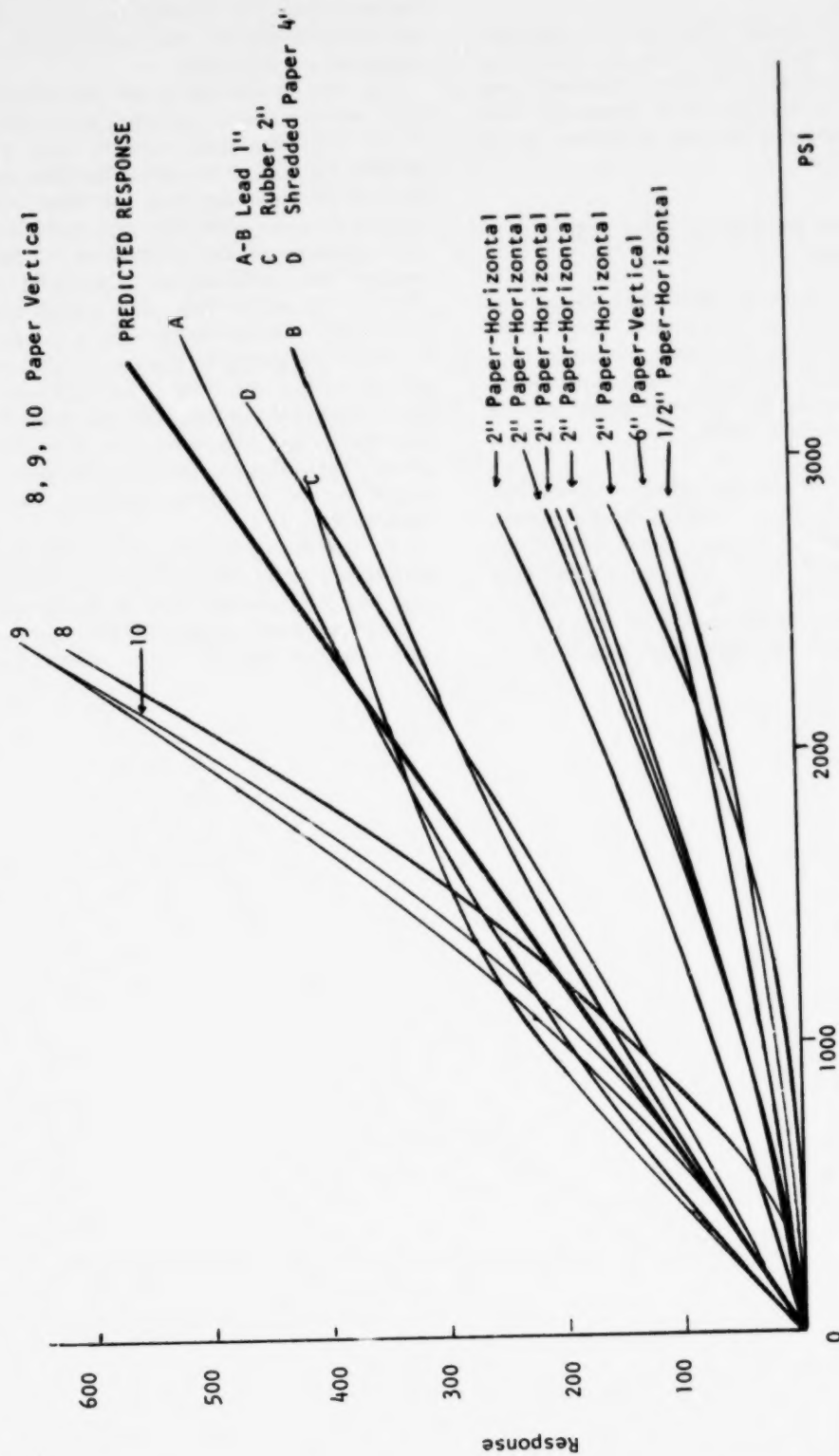


FIGURE 7
Response of Strain Gage to Loads From Various Materials

it-carried the main load. The curve obtained for shredded paper was found to be closest to that predicted.

The results indicated clearly that the gaged liner plates as used in the tests were not suitable for measurements of the wall forces produced during compaction. The shortness of the project precluded further investigation of different approaches utilizing the same principle.

3. Chamber Wall Measurements Using Penetration Gages

After the electrically gaged liner plates were, within the scope of this project, found to be unsuitable for chamber-wall force measurements, a different approach was tried. A gage assembly was constructed utilizing the experience gained with the ball penetrometer gages for internal force measurements.

Two plates, of an area equivalent to the high pressure ram face (16 x 20 inches), were constructed. Balls were placed at regular intervals between the plates. Only one of the two plates was designed to be penetrated; the other was used to distribute the load. The penetration plate was constructed from 1/8-inch aluminum sheeting. The load distributing plate was

made from a 3/16-inch steel sheet. The entire assembly, including the balls, was 9/16-inch thick. The penetration gage assembly contained 252 balls, and therefore allowed peak measurements of the normal force at 252 points.

In order to maintain proper ball spacings, the plates were fastened at two edges to a narrow filler plate. This filler plate extended only 1/4-inch between the edge of the plates. The filler was also used to minimize the entry of waste materials between the plates during the compaction process.

Calibration of the indentations of the ball elements was performed in a laboratory testing machine. A known load was applied and the indentations were read by microscope to a precision of about ± 200 pounds for loads above 2,000 pounds. The precision of the readings was higher for lesser loads. The over-all accuracy of the measurements over the whole range of pressure was better than 10 percent. The calibration curve shown in Figure 8, was found to be somewhat non-linear, but quite reproducible.

To test the applicability of this gage to refuse compaction, several experiments were carried out. Only one plate assembly, next to the high-pressure ram face, was used in most cases. However, in a few cases two plate assemblies were inserted into the

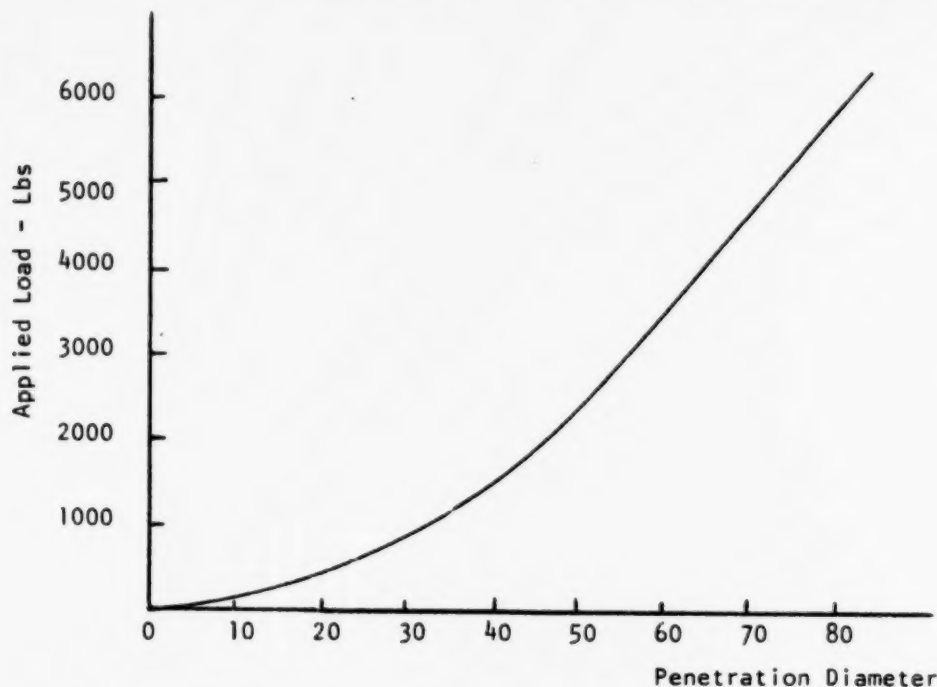


FIGURE 8
Penetration Gage Calibration Curve

compaction chamber, one on the top of the high pressure ram, and the other directly opposite the same ram adjacent to the cover plate of the press. After the compaction experiments were completed the plates were removed from the press and analyzed.

Analysis of the plates and their indentations showed that the load values were slightly higher than they should have been. This effect can be accounted for by the fact that the ball area, which is the sensing area, was stiffer than the area between the balls. The close spacing of the balls, and the properties of the steel plate acting as a non-rigid diaphragm, minimized this effect. The calibration curves obtained for different waste materials were all similar.

Although the investigation and application of the above method could not be fully explored, the results showed clearly that valuable information can be obtained from it. The results of the penetration gage measurements obtained for refuse and their interpretation are discussed in the section on the compaction of wastes, Section Three.

SECTION TWO—DESCRIPTION OF THE SOLID WASTES USED IN THE STUDY

This section describes and discusses the properties of the uncompacted wastes which were subjected to compaction. It includes a description of different types of (I) residential wastes as delivered by truck and of (II) synthetic refuse samples specially prepared for this study. The composition, moisture content, and densities of the uncompacted refuse are discussed in some detail.

I. RESIDENTIAL REFUSE

For the purpose of this report the household refuse used during the compaction program has been subdivided into six different categories:

- a) Residential Refuse—loose
- b) Residential Refuse—shredded
- c) Residential Refuse—in paper sacks

- d) Residential Refuse—in plastic sacks
- e) Oversized Wastes (refrigerators, furniture, stoves, washing machines, appliances), and
- f) Mixtures of oversized wastes and household refuse

The above subdivision has been made in view of both the existing collection practices and the differences encountered in the compaction behavior of the wastes delivered in different forms.

1. Composition and Moisture Content of Loose, Sacked, and Shredded Residential Wastes

The composition and moisture content of the individual samples of loose, shredded, paper-sacked and plastic-sacked household refuse used for testing varied appreciably. However, the effects of composition and moisture content on the compaction of wastes were found to be pronounced only for extreme variations introduced either by drastic seasonal changes in the refuse composition or by weather conditions which increased the water content of the wastes.

In the over-all, the waste mixtures from households were of similar composition during the same season irrespective of whether the mixtures were confined in paper or plastic sacks, shredded, or delivered in the loose state. The moisture content of the various mixtures, however, varied appreciably with weather conditions. It was highest for loose refuse during rainy days, while rain had little or no effect on the moisture content of sacked refuse.

a) Composition of Winter and Spring Refuse

Two types of seasonal refuse were subjected to compaction during the testing period, which lasted from January 28, 1969, through April 1969. The two types are classified as winter refuse and spring refuse.

The composition of these two types of refuse varied markedly. The winter refuse was largely

TABLE 9
Composition of Dry Winter Refuse

Components in Percent of Total Weight (averages)						
PAPERS (Solids and absorbed liquids) %	GLASS & CERAMICS %	METALLIC WASTES %	FOOD (Solids and bound water) %	PLASTICS %	TEXTILES (Solids and absorbed water) %	RUBBER, DIRT CHEMICALS, ETC. %
70	6	6	5	3	3	7

composed of paper products. The paper content of the individual loads was estimated to range from about 50 to 80 percent by weight of the total refuse. An estimate of over-all composition of dry winter refuse is given in Table 9.

In order to obtain some estimate of the over-all composition of the spring refuse, samples were taken over a period of days and separated manually into different components. The composition, as identified for 18 samples, each of an average weight of 176 pounds, is given in Table 10.

TABLE 10
Composition of Springcleaning Refuse

Components in Percent of Total Weight (averages)						
PAPERS (Solids and absorbed liquids) %	YARD RAKINGS, Dirt (& moisture) %	GLASS & CERAMICS %	FOOD (Solids and bound water) %	TIN CANS %	RAGS, SHOES & Moisture %	PLASTICS %
47.0	17.1	12.2	9.6	9.3	2.5	2.4

The refuse received from the City of Chicago during the spring period contained a large proportion of yard rakings and dirt which were absent in the winter refuse. In addition, it contained also more glass, food, and metallic wastes but appreciably less paper.

b) Moisture Content of Loose and Sacked Residential Refuse

The over-all moisture content of the winter and spring refuse was found to vary. In the absence of snow or rain the refuse containing yard rakings, irrespective of whether delivered loose or in sacks, was usually more moist than the winter refuse. However, both types of refuse could contain dry, moist, and wet portions.

Large differences in moisture content between sacked and loose refuse were found only when the refuse was exposed to snow or rain. Both paper and plastic sacks were found to be an effective means of preventing precipitation from entering the refuse. Loose refuse, on the other hand, was always found to be affected.

Snow or light rain of short duration affected mainly the surface portion of loose refuse. Heavy rain or light rain of long duration raised the moisture content of the exposed refuse to a degree where water became the major constituent of the refuse.

Moisture determinations of samples of loose household refuse during dry, snowy, and rainy weather are given in Table 11. The values for samples taken from the same load of refuse are days or from different loads.

The moisture content of loose and sacked refuse samples taken during dry weather conditions varied from 10 to 35 percent by weight of the total refuse. Variations of up to 20 percent were found in samples taken from the same load. The highest moisture content of the dry weather refuse was associated with

samples of high food content.

The moisture content of refuse exposed to snow was, as a rule, higher than that of dry weather refuse only for samples in direct contact with snow. Variations in the moisture content (see Table 11) between 12.5 weight percent for dry refuse to 24.0 weight percent for refuse wetted by snow were recorded.

The moisture content of loose refuse was always high after exposure to rain. The lowest measured value was 25 percent of total weight of the total refuse.

However, the reported values for very wet refuse are lower than the initial liquid content of the delivered refuse. Higher values would have been obtained if the total liquid content, before runoff of excessive water, had been determined.

c) Moisture Content of Shredded Residential Wastes

One truckload of shredded refuse was received from Madison, Wisconsin. It appeared to consist primarily of a high proportion of shredded paper products. However, it also contained a limited amount of non-shredded materials such as squashed metal cans, shoes, and rubber which were separated during the shredding process by the Heil-Gondard shredder, and subsequently added to the shredded material.

TABLE 11
Moisture in Residential Refuse

No. of Samples	Drying Temp. (°F.)	Drying Time (hours)	Moisture in Percent of Total Weight			Comments
			% Maximum	% Minimum	% Average	
4	200 250	16 4	22.5	10.0	14.4	Loose & Sacked Refuse Dry weather (Dry, moist and wet samples)
5	200 250	16 4	27.5	12.5	16.5	
5	200	21.5	22.5	10.0	17.5	
1	250	11	-	-	17.5	
5	200 250	16 4	25.0	17.5	23.0	Loose & Sacked Refuse. Dry weather (moist & wet samples) High food content
5	200 250	16 4	35.0	15.0	23.5	
4	250	20	22.5	12.5	18.1	Loose Refuse. Snow, (dry, moist and wet samples)
1	250	18	-	-	21.5	
1	250	10	-	-	24.0	
5	200 250	16 4	40.0	25.0	28.5	Loose Refuse. Rain, (wet and very wet samples)
5	200 250	16 4	50.0	35.0	44.5	

TABLE 12
Moisture in Shredded Residential Refuse

No. of Samples	Drying Temp. (°F.)	Drying Time (hours)	Moisture in Percent of Total Weight			Comments
			% Maximum	% Minimum	% Average	
7	250	7 to 20	12.5	7.5	10.7	One day delivery

The shredded material appeared to be rather dry. The results of the moisture determinations of seven samples taken from the same load of shredded household refuse are given in Table 12.

The relatively small variations in moisture content between 7.5 and 12.5 percent of different samples indicate a greater uniformity of the moisture distribution in shredded than in unshredded refuse. Moisture determinations were made with fresh as well as stored refuse. The lowest moisture content samples represent refuse stored over a period of days in the test building.

2. Densities of Loose, Sacked, and Shredded Residential Wastes

The densities of individual samples of household refuse delivered during the period of testing varied appreciably. Since the density of a given load of refuse is determined both by the density of the individual components and by the ratio of void to occupied space in a given volume, and since both of these factors can vary, it is not surprising that large variations in densities can be encountered.

In order to obtain as much information as possible about the densities of residential wastes, an

appreciable number of volume and associated weight measurements were taken from samples of the incoming household refuse throughout the testing program. A summary of the computed densities of household refuse for loose, paper-sacked, and shredded refuse is given in Table 13.

The densities of the loose household refuse, containing both wet and dry refuse, were found to range from 3.8 to 15.9 pounds per cubic foot. The lowest value, 3.8 pounds per cubic foot, was obtained with very dry, lightweight refuse; the highest, 15.9 pounds per cubic foot, for rather wet refuse exposed to rain.

Density values separated to reflect the effect of moisture are shown in Table 14. They indicate that the average density of wet refuse samples (10.5 lbs/cuft) was about 3 pounds higher than the average density of the dry refuse (7.6 lbs/cuft).

The densities of the damp, spring-cleaning refuse reflect both the presence of low density materials such as dry leaves and dry clippings, and higher density wet solids such as wet dirt. As a result, the average density of the spring-cleaning refuse appears to be more comparable to the ordinary dry refuse than to the wet refuse which either contained a high

TABLE 13
Densities of Residential Refuse

No. of Samples	DENSITIES (lbs/cuft)			COMMENTS
	Maximum	Minimum	Average	
204	15.9	3.8	9.0	Household Refuse-Loose, (contained appreciable number of samples of high water content)
27	10.1	4.8	7.2	Household Refuse in Papersacks
34	11.0	8.2	9.6	Shredded Household Refuse (one day delivery)

TABLE 14
Effect of Moisture on the Densities

No. of Samples	DENSITIES in lbs/cuft			COMMENTS
	Maximum	Minimum	Average	
106	15.9	7.1	10.5	Wet Refuse
12	13.3	5.5	8.0	Damp Springcleaning Refuse (containing clippings, leaves, and dirt)
86	11.0	3.8	7.6	Dry Refuse

proportion of food wastes or was exposed to rain.

The densities of household refuse contained in paper and plastic sacks were close to those obtained for loose dry refuse (compare Tables 13 and 14). The densities ranged from 4.8 to 10.1 pounds per cubic foot; the average density, determined for 27 samples, was 7.2 pounds per cubic foot.

The densities of dry shredded household refuse (Table 13), varied only between 8.2 and 11.0 pounds per cubic foot. Since all samples came from the same load of refuse, larger variations are to be expected for samples taken over a longer period of time.

The average density of the shredded refuse was found to be 9.6 pounds per cubic foot, 2 pounds higher than the average value of the dry, unshredded refuse. Since the moisture content of the shredded refuse was low (see Table 12), and since it did not contain a large amount of high density components, the increase in over-all density of the shredded refuse was associated with the reduction of void space in the refuse.

3. Composition, Moisture Content, and Densities of Oversized Wastes

The composition, moisture content, and densities of oversized wastes differ from those of the other types of household refuse. The differences in composition arise primarily from an increased amount of specific waste components such as metals, wood, and textiles, and from the absence or drastic reduction of other components such as food wastes and papers. Although no attempts were made during the present study to determine the properties of the oversized wastes, it can be stated that, as a rule, the densities of these waste mixtures are appreciably higher and their moisture content much lower than that of ordinary household refuse.

II. SYNTHETIC SAMPLES OF RESIDENTIAL WASTES

One of the major variables affecting the properties of wastes is the continuous change of the refuse composition. In order to eliminate this variable, a series of experiments was made with refuse mixtures of known composition. In addition, synthetic samples of known composition were also prepared to test the effect of single waste components, such as moisture, on the compaction of wastes. The types of samples used in the test program were:

- a) Synthetic mixtures of residential wastes—loose
- b) Synthetic mixtures of residential wastes—in paper sacks
- c) Synthetic mixtures of papers and water

- d) Mixtures consisting of two components, and
- e) Selected individual refuse components, including papers, metals, glasses, rubber, bedsprings, food wastes, ashes, and sawdust.

I. Synthetic Residential Waste Mixtures

a) Composition

Two slightly different types of synthetic mixtures were prepared to simulate the composition of dry household refuse. They were then placed into paper sacks or used in the loose state and subjected to different compaction conditions. The samples of these mixtures were used in compaction experiments designed to eliminate variables introduced by different refuse compositions.

The composition of these two mixtures is given in Table 15. The choice of the individual waste components by type and proportion was based on estimates of the over-all composition and moisture content of wastes delivered by the City of Chicago during the winter months.

Both types of mixtures contained a high proportion of paper products, 60 percent by weight, to simulate the high paper content of the city wastes. The main difference with respect to the other components was that mixture (1) contained a few percent more food and water than mixture (2). On the other hand, mixture (2) contained larger amount of construction wastes.

In order to simulate an over-all liquid content of dry household refuse similar to that determined from moisture experiments with city-delivered refuse (see Residential Refuse), liquids were either added separately or introduced through solid wastes which contained bound or absorbed water.

The food wastes added to the mixtures were restricted to vegetables and fruit. These contained a high amount of bound moisture. The following food items were used: tomatoes, oranges, grapefruit, lettuce, potatoes, celery, green peppers and okra. They were partially squashed and then added to the synthetic mixture.

b) Moisture Content

The total moisture content of the mixtures 1 and 2 was obtained by taking into account the moisture absorbed by the solid components from the atmosphere and the moisture subsequently introduced by the addition of liquids and food wastes.

Moisture in food wastes

The amount of moisture introduced through the addition of vegetables and fruits was estimated to be about 80 percent of the actual weight of the food

wastes added to the mixtures. This estimate is based on published data* given for the average moisture content of the edible part of the wastes used in the synthetic mixtures:

	Moisture
Tomatoes:	94.1% of edible portion
Oranges:	87.2 "
Grapefruit:	88.8 "
Lettuce:	94.8 "
Potatoes:	77.8 "
Celery:	93.7 "

* Methods in Food Analysis, Maynard and Joalyn, New York, 1950, p. 48. Academic Press Inc.

Thus, it appears safe to assume that at least 80 percent of the weight of the food wastes added was moisture. This means that the combined moisture content of the mixtures due to direct water addition and through food wastes was about 12.4 percent by weight for mixture (1) and about 7.8 percent by weight for mixture (2).

Absorbed moisture

Moisture is introduced into wastes not only by the addition of liquids and food or garden wastes, but also through other solid components which absorb moisture from the atmosphere.

In terms of moisture absorbing capabilities, paper products rank first among the waste components.

TABLE 15
Composition of Synthetic Refuse Mixtures (1) and (2)

COMPONENTS	Mixture (1)	Mixture (2)
	Percent of Total Weight	Percent of Total Weight
Newspapers	18.0%	18.0%
Cardboard & Corrugated Board	15.0	15.0
Junk Mail	9.0	9.0
Magazines	9.0	9.0
Brown Paper	4.5	4.5
Plastic Coated Papers	3.0	3.0
Tissue (absorbent)	1.5	1.5
	<u>60.0%</u>	<u>60.0%</u>
Glass & Ceramics	8.0	8.0
Metal Cans (beer & aerosol)	8.0	8.5
Food Wastes (fruit & vegetables)	8.0	6.0
Liquids (water)	6.0	3.0
Construction Wastes (plaster, bricks, wood)	3.5	8.0
Plastic Wastes	3.5	3.5
Textiles	1.0	1.0
Rubber	0.5	0.5
Leather	0.5	0.5
Dirt	0.5	0.5
Oils	0.5	0.5
	<u>40.0%</u>	<u>40.0%</u>

These products are also present in large quantities. An estimate of the absorbed moisture introduced into waste mixtures through exposure to a humid atmosphere therefore has to be based primarily on a knowledge of the absorptive properties of the papers present in the mixtures.

In order to obtain a reasonable estimate of the moisture in waste papers, several series of moisture determinations were carried out during the present study (see Table 17).

Based on these moisture determinations, it is estimated that the absorbed moisture introduced through papers amounts to about 10 per cent of the weight of the paper mixture. This amount was found to be close to the absorptive capacity of papers when exposed to relatively dry atmospheres.

The total moisture in the synthetic mixtures (1) and (2) (added liquids, food moisture, and absorbed moisture in papers) is, therefore, estimated to be about 20 and 13 per cent of the total weight, respectively. It is, of course, clear that other refuse items, such as textiles, also contained absorbed water.

c) Densities

The densities of the two types of synthetic mixtures varied only slightly. The average density for mixture (1) was found to be 7.9 pounds per cubic foot, and 7.6 pounds per cubic foot for mixture (2).

2. Synthetic Samples of Papers and Water

A series of samples containing only paper products and a known amount of water was prepared to investigate the effects arising from the interaction of moisture and papers during and after compaction. In addition, several series of experiments were carried out to determine the moisture contained in papers before the addition of water.

The paper products were specifically investigated on their own because they represent the major component of residential wastes. Furthermore, papers exhibit pulping and expansion characteristics in the presence of moisture, which determine to a large

degree the compaction properties of residential waste mixtures.

a) Composition

To investigate the influence of different degrees of moisture on compaction, several samples of paper mixtures and several samples containing only newspapers were used. Newspapers were selected to obtain information relevant to highly absorbent papers. The composition of the paper mixtures is shown in Table 16.

The paper mixtures were used in the compaction experiments either after predrying or without drying. A predetermined quantity of water was always added to the mixture. In total, 13 samples containing from about 10 weight per cent to about 50 weight per cent of water, were prepared.

Finally, 14 newspaper samples containing either (1) loose sheets or (2) bundles of papers were also wetted to simulate a moisture content similar to that of the paper mixtures.

b) Absorbed moisture in papers

In addition to the water which was added to the paper samples, some samples contained already absorbed moisture before the introduction of water.

In view of the importance of the interaction of moisture and papers and their large effect on compaction, a number of experiments were made to obtain information about moisture absorbed from the surrounding atmosphere by the papers used. This investigation was primarily qualitative in nature. It was designed to provide over-all information about moisture absorption and, together with other information, to provide an important input for the evaluation of the compaction process.

The moisture determinations were carried out with samples weighing 20 pounds before drying (individual papers) and up to 100 pounds (paper mixtures). The papers were distributed on perforated trays, resting on a cart which could be wheeled in and

TABLE 16
Composition of Synthetic Paper Mixtures

Components	Percent of Total Weight
Newspapers	32.5
Cardboard & Corrugated Board	25.0
Junk Mail	15.0
Magazines	15.0
Brown Paper	7.5
Plastic Coated Papers	5.0
	100.0

out of a gas heated oven (Dry-Sys G3 4-8 model).

In this oven, a pressure blower propelled the heated air in a flow pattern throughout the drying chamber, gaining access to the papers both on top of the trays and through the bottom perforations. A temperature controller was used to keep the temperature constant within a few degrees for the duration of the experiments. A low temperature of 200°F. was used during night drying periods. However, each sample was heated in addition for at least several hours at 250°F. during the daytime.

The paper samples were, in most cases, subjected to drying until weight constancy within the experimental error was achieved. Since nonprecision

weighing equipment was used, and re-absorption of water vapor during drying and weighing could not be eliminated, the error in the moisture determinations could have been as high as 25 percent.

The results of the moisture determinations in different papers and paper mixtures are presented in Table 17.

The apparent moisture content of plastic coated papers, magazines, and cardboard was found to lie between 2 and 5 percent of the total weight. For newspapers, it was found to be between 4 and 26.0 weight percent, and for the paper mix, between 4.4 and 12.1 weight percent. The visual appearance of the papers, with the exception of the newspapers

TABLE 17
Moisture in Papers

No. of Samples	Drying Temp. (°F.)	Drying Time (hours)	Moisture in Percent of Total Weight			Comments
			% Maximum	% Minimum	% Average	
6	250 200	3 16	18.0	8.0	12.0	Newspapers
6	250	9	36.0	4.0	13.0	Newspapers
5	250	8	5.0	2.5	4.5	Plastic Coated Papers
6	250 200	3 17	4.0	2.0	2.3	Magazines
5	250 200	3 17	5.0	2.5	4.0	Cardboard
9	~ 300	2 - 4	13.1	4.4	7.1	Paper Mixtures (a)

(a) Paper Mixture:

Weight Percentage

Newspapers	32.5
Cardboard	25.0
Junk Mail	15.0
Magazines	15.0
Brown Paper	7.5
Plastic Coated	5.0

containing 36 weight percent moisture, was that of dry paper.

It should be emphasized that the moisture values presented in Table 17 are probably lower than the actual moisture content of the papers. In addition, the moisture determinations were made with papers stored for various lengths of time in a heated building. Much higher values are to be expected for papers exposed to high humidity.

It should also be remembered that the moisture content of papers will be greatly affected not only by variations in humidity but also by the various chemical treatments given to the papers. A uniform value of moisture for papers, therefore, cannot be obtained even if the atmospheric conditions are kept constant. It appears, however, that paper mixtures of the type found in residential wastes absorb moisture under relatively dry conditions to a level of about 10 percent or more of their weight.

3. Synthetic Samples of Papers and Adhesive

Paper mixtures of the same composition as that given in Table 16 were also used in a short series of tests designed to gauge the effect of adhesives on the binding properties of wastes. Since household wastes usually contain moisture and are largely composed of papers, the types of adhesives chosen were water soluble with paper adhesive properties.

Swift and Company suggested and supplied the following adhesives:

- a) Polysaccharide base, 55 percent solids plus 45 percent water.
(Adhesive 45A)
- b) Protein base, 55 percent solids plus 45 percent water.
(Adhesive 45C)
- c) Cellulose base, 60 percent solids plus 40 percent water.
(Adhesive 45B)
- d) Cellulose base, 45 percent solids plus 55 percent water.
(Adhesive 45D)
- e) Jet dried blood, powder, protein base.

Another adhesive was supplied by Neville and Company. It consisted of a hydrocarbon base dissolved in mineral spirits (70 percent solids plus 30 percent mineral spirits).

All adhesives used in the program were further diluted prior to application. The adhesives used with paper mixtures contained 15 percent solids. Adhesives used for the coating of paper sacks contained about 20 percent of solids.

4. Selected Samples Containing One or Several Known Refuse Components

In order to obtain information about the compaction properties of specific refuse items of interest, a number of experiments were made with refuse components specially secured for this purpose.

Selected refuse components investigated on their own, or in combination, included items such as: 1) rubber tires, 2) bedsprings, 3) incinerator ashes, 4) wood shavings and wood chips, 5) metal cans, 6) refrigerators, stoves and appliances, 7) plastic scrap, 8) dry paper, 9) wood shavings and vegetables, 10) wood shavings and meat scraps, 11) shredded rubber and refuse, 12) wood chips and refuse, 13) oversized wastes and refuse, and others.

SECTION THREE—COMPACTION OF REFUSE

The main objective of this part of the experimental study was the gathering of information and the evaluation of the compaction properties and bale properties of different types of refuse subjected to the same or different compaction conditions.

I. PROCEDURE

To achieve the above objectives, several series of experiments were carried out, testing either the influence of refuse composition or compaction variables or both. In addition, specific variables likely to affect the properties of the compacted refuse were investigated on their own.

The compaction properties and properties of the compacted bales of residential wastes were investigated extensively. This was done in view of the importance of acquiring realistic information, not only about the over-all compaction properties of household wastes, but also about the effects arising from the continuously varying compositions encountered in actual day-to-day operations.

To reflect different collection practices, series of experiments were made with household refuse delivered either 1) loose, or 2) sacked in paper or plastic bags, and 3) with shredded refuse. They were subjected to different compaction pressures, applied for different time periods, and their characteristics were determined both with respect to their properties during pressure application and after the removal of pressure from the compacted bales.

In addition to the experimental investigation carried out with household refuse of random composition, several series of experiments were also made with synthetic samples of a predetermined composition.

The synthetic samples were used to investigate compaction variables on their own, and also for the purpose of gaining information of the properties of

specific waste components and waste mixtures. Synthetic samples were also used in experiments designed to test the effect of factors such as adhesives and moisture on the bale stability.

The synthetic samples used in the test program consisted of mixtures of 1) synthetic household refuse—loose, 2) synthetic mixtures in paper sacks, 3) water-paper mixtures containing different amounts of moisture, and 4) different two-component mixtures and selected refuse components of special interest. The effects of compaction variables for both a range of pressure and time period of pressure application were studied with samples of the same composition. The effects associated with the addition of special waste components were investigated under the same compaction conditions, using samples of successively different compositions.

The compaction press, press operation, and measurements of the press parameters are described in detail in Section One of this chapter. In brief, the individual samples of refuse were subjected to compaction in a hydraulically operated three-stroke press (Fig. 3). The main function of the first and second ram of the press was the gathering of the refuse from the large charging box into a more confined space of about 7.8 cubic feet. The maximum force which could be exerted by these two rams was only 94 and 573 psi, respectively. The final compaction of the refuse was accomplished by the third ram which could exert pressure up to about 3,500 psi.

The pressure applied by the third ram was varied during individual runs of compaction. Samples were subjected to pressures of about 500, 750, 1,000, 1,500, 2,000, 2,500, 3,000, and 3,500 psi. Some samples were also compacted at higher pressures, about 6,000 psi, by concentrating the available force of the high pressure ram on a smaller surface area. In each case the exerted pressure of the third ram was measured and recorded during the entire ram travel. The equipment used provided records not only of the applied pressure but also of the time of pressure application as well as of the distance the ram moved during the pressure application. The time required to compact the bale during the final compaction (3rd ram) was, in normal fast runs, about 17 seconds.

Initially, a number of runs were made to determine the over-all compaction properties of the residential wastes. The delivered wastes were separated into different loads and their weights and volumes were measured. These loads were then subjected to compaction and the volume reduction in the compaction chamber was determined as a function of applied pressure. It was found that a

volume of about 25 cubic feet and a weight of about 200 pounds was usually necessary to produce bales of convenient sizes. Since the standardization of the volume was found to be less cumbersome than standardization of the weight, most experiments were carried out with samples of about 25 cubic feet. However, experiments were also made with samples of different volumes and standardized weights.

However, irrespective of whether the volume or the weight of the uncompacted refuse was kept constant throughout an experimental series, both the volume and the weight were determined for any given sample subjected to compaction. This was necessary in order to develop a number of important inputs such as the densities of the incoming refuse, the volume reduction ratios of the compacted refuse, and the densities of the compacted bales.

The volume of the bales formed in the compaction chamber was obtained from measurements of the length and width of the enclosure formed in the press by the first and second ram after full extension, and from the determination of the position occupied by the third ram which provided a measure of the height of the bale (See Section One). Since the dimensions of the enclosure formed by the first and second ram were always fixed, the only dimension which had to be determined in individual runs was the height of the bale. The dimensions, in inches, of the bale in the compaction chamber were, therefore, in each case: 20 x 16 x variable.

The densities of the bales in the compaction chamber were determined from weight measurements taken after removal of the bale from the chamber, and from determinations of the volumes of the bales inside the compaction chamber.

Weight measurements outside the compaction chamber were made since it was found that the weight of the baled refuse was often less than that of the initial load of the loose refuse. This finding indicated that weight losses occurred during compaction. However, the bale volume had to be determined inside the chamber and during pressure application since removal of pressure from the bale always resulted in an immediate expansion of the bale volume.

The expansion in volume of the compacted bale, after removal from the compaction chamber, was usually measured over a period of 24 hours and sometimes up to 72 hours. These values were then used to compute the densities of the bales after removal from the press.

Further details of the experimental investigation dealing with the compaction of wastes and the results

obtained are given in the two following sections: II. Compaction of Residential Wastes, and III. Compaction of Synthetic Refuse.

II. COMPACTION OF RESIDENTIAL WASTES

In order to obtain information about the compaction properties of wastes discarded by households, samples prepared from different truckloads of refuse were subjected to compaction. Since sampling was done throughout the testing period, it allowed an assessment of the variations to be encountered with respect to compaction properties in actual day-to-day operations and as a result of seasonal changes in refuse composition.

The qualitative properties of the uncompacted household refuse subjected to compaction have been discussed previously in Section Two. It has to be kept in mind that the properties of the individual samples used in this part of the study varied from sample to sample. However, the variations with respect to composition and moisture content were largest for refuse received during the two different seasons, winter and spring, and for refuse exposed to rain as compared to dry weather.

The experimental results are presented separately for refuse delivered in different forms: 1) residential refuse, loose; 2) residential refuse in paper and plastic sacks; 3) residential refuse, shredded; and 4) oversized wastes. This was done to highlight differences in compaction properties other than the inherent variations in composition originating at households, and to emphasize the influence of collection practices.

1. Residential Refuse—Loose

Approximately 200 different samples of loose residential wastes were compacted during the testing program. They contained refuse discarded by households during winter and early spring. Their moisture content ranged from very dry to very wet. Some samples were covered with snow.

Different samples were subjected to pressures of about 500, 750, 1,000, 1,500, 2,000, 2,500, 3,000, and 3,500 psi, respectively. The decrease in volume was measured during compaction as a function of applied pressure. Subsequently, the expansion in volume of the compacted bales, outside the compaction chamber, was measured over a period of time. The densities of the compacted refuse during and after compaction were determined. The results of the experimental study and the evaluation of these results are presented in the following sections.

a) Volume Reduction During Compaction

The reduction in volume by compaction was accomplished in several steps. Initially, any given load

of refuse was gathered by the first ram of the press into a space occupying 23.3 cubic feet. Subsequently, the volume of the refuse was reduced to about 7.8 cubic feet by the action of the second ram of the press. The final compaction from 7.8 cubic feet to its lowest volume was then accomplished by the advancement of the high pressure ram which confined the refuse into a bale of the dimensions of 20 x 16 x variable inches. The only variable dimension (height of the bale) was determined in each experiment from electronic measurements of the third ram deflection.

An example of the recorded third ram deflections as a function of applied pressure, and the respective change in bale height, is shown in Figure 9. The upper curve was obtained with eight different samples prepared from the same load of refuse, each weighing 200 pounds, which were compacted at different pressures. It can be seen that the superimposed curves of the individual runs coincide above a pressure of about 1,000 psi, indicating the great similarity in properties of the individual samples. Differences in curvature below 1,000 psi, however, show that the compressibility of the samples was not the same over the whole range of pressure. The lower curve in Figure 9 shows the ram deflection of a sample of greater weight.

Curves which could not be superimposed were obtained for equal weight samples prepared from loads of refuse of different properties. However, the composite curve in Figure 9 represents a good example of the over-all change in bale height and therefore in bale volume of individual samples of both similar and different properties. For example, the bale height always decreased with an increase in unit pressure over the whole pressure region tested. The decrease was also always more pronounced in the region below 1,000 psi than above 1,000 psi.

As mentioned previously, experiments were carried out with samples constant in either volume or weight. In addition, experiments were made with samples of different volume and weight. Variations in volume of the uncompacted refuse ranged from about 15 to 45 cubic feet, and in weight from about 130 to 400 pounds.

In most cases the volume of bales in the compaction chamber, when compacted at 3,500 psi from an initial load of 25 cubic feet, was found to be in the region of 1.6 to 2.6 cubic feet. The largest bale of about 4.0 cubic feet was produced from a 45-cubic foot sample. The smallest bale, 1.1 cubic feet, was obtained from a load of about 25 cubic feet. The volume reduction ratios of different types of refuse subjected to the same pressure varied from about 7:1 to about 23:1. Volume reduction ratios

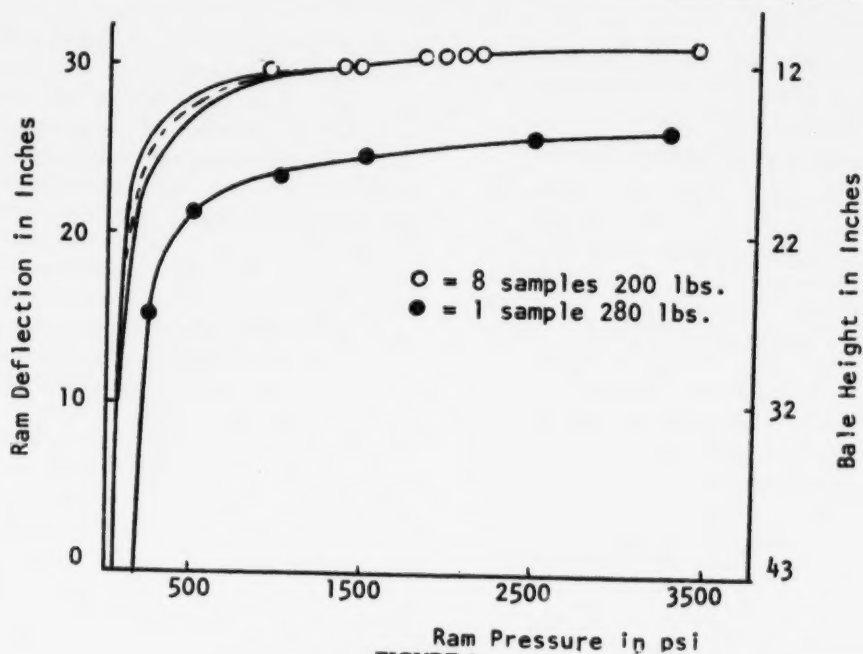


FIGURE 9
Residential Wastes—Loose. Ram Deflection
During High Pressure Compaction

calculated for different bales compacted at about 3,500 psi are given in Table 18.

It can be seen that the variations in volume reduction encountered with household refuse were as high as 300 percent. It has to be pointed out, however, that the minimum volume reduction by a factor of 7 was obtained only in two cases in which yard cleaning refuse of high dirt content was compressed. Similarly, the maximum reduction in volume by a factor of 23 was obtained only once. Even values of 18:1, the next highest value, were found only in a few isolated cases. For practical purposes it is therefore more reasonable to expect variations in the range of 8:1 to 18:1.

The volume reduction ratios computed for refuse samples compacted at a lower pressure than 3,500 psi are given in Table 19.

A comparison of the volume reduction ratios shows that the increase in volume with decrease in pressures was not systematic. This is understandable

if one takes into consideration that the variations in volume reduction of different samples can be very large and that the decrease in volume with pressure is relatively small at higher pressures (see Fig. 9).

In order to establish the cause of the large variations in volume reduction of different waste samples two possibilities were considered: the compressibility of the solid portion of the refuse which could vary from sample to sample and the variations in void space which could easily account for large differences in volume reduction ratios. In both cases the refuse densities of the uncompacted refuse and the subsequent reduction in volume should be interrelated. This interrelationship and the conclusions drawn from it are discussed in the next section.

b) Effect of Incoming Densities on Volume Reduction

Differences in properties which could affect the magnitude of volume reduction can be associated

TABLE 18
Volume Reduction Ratios During Compaction of Loose
Residential Refuse Compacted at about 3500 psi

No. of Samples	Maximum	Minimum	Average
60	23 : 1	7 : 1	12.8 : 1

TABLE 19
Volume Reduction Ratios of Different Bales Compacted at
Different Pressures

No. of Samples	Maximum	Minimum	Average	Compaction Pressure (psi)
15	15.0 : 1	6.3 : 1	9.1 : 1	2300 - 2500
27	17.7 : 1	6.8 : 1	11.6 : 1	1850 - 2000
8	13.5 : 1	7.2 : 1	9.7 : 1	1400 - 1500
13	12.0 : 1	7.0 : 1	8.9 : 1	850 - 1000

TABLE 20
Volume Reduction Ratios of Loose Household Refuse as a
Function of Incoming Densities and Compaction Pressures

Samples	Densities of Loose Refuse (averages in lbs/cuft)	Volume Reduction Ratios (averages)	Compaction Pressure (psi)
31 29	6.7 10.8	15.0 : 1 9.1 : 1	3000 - 3500
14 28	6.9 10.8	13.2 : 1 9.5 : 1	1850 - 2500
3 5	6.8 10.6	12.0 : 1 8.3 : 1	1350 - 1500
8 13	7.6 10.0	9.8 : 1 8.1 : 1	650 - 1000

either with differences in initial void space or compressibility of the components in a given refuse load.

In cases in which the solid items in the refuse are more difficult to compact, it is to be expected that the remaining void space in the compacted bale is larger than in bales produced at the same pressure from refuse loads which can be easily compacted. Variations in void space left in the bales could account, therefore, for differences in the volume of the refuse bales. However, the differences in void space left in the compacted household refuse were generally much too low to be able to account for the large variations in volume reduction. On the other hand, large variations were observed in initial void space of the loose refuse. These, therefore, could more easily account for the differences found in the reduction ratios of different refuse samples.

The densities of loose refuse samples containing materials of similar densities but varying amounts of

voids should vary in direct proportion to the contained void space. Similarly, the volume reduction ratios of samples containing materials of comparable compaction properties should vary with void space. It is to be expected, therefore, that a direct proportionality between incoming densities and volume reduction ratios will be found in all cases in which the difference between the refuse samples is based only on a varying amount of void space.

In order to test whether differences in void space are responsible for the differences found in the reduction ratios, an attempt was made to determine the relationship between the densities of the uncompacted refuse (see Section Two) and the volume reduction achieved by compaction. The results of this evaluation are presented in Table 20.

The low density values of 6.7 to 7.6 are averages for loads which had densities in the range of 3.6 to 8.0 pounds per cubic foot. The high values of 10.0 to 10.8 are averages for loads having loose densities in

the range between 8.0 and 15.9 pounds per cubic foot.

It can be seen that the reduction in volume of the low density refuse was higher than the volume reduction of the high density refuse, irrespective of the pressure applied. The average volume reduction of the high density refuse varied at different pressure only between 8.1 and 9.5 whereas the volume reduction of the low density refuse varied from 9.8 to 15.0. The difference in the magnitude of the volume reduction ratios for low and high density refuse was more pronounced at pressures above 1,000 psi.

The interrelationship between the densities of the loose refuse and the associated volume reduction ratios appears to be quite striking. For example, at 3,500 psi, the increase in density by a factor of about 1.61—from 6.7 to 10.8 pounds per cubic foot (first row of Table 20)—was accompanied by a nearly equivalent decrease in the volume reduction ratio from 15 to 9.1. In the other pressure ranges above 1,000 psi, an increase by a factor of about 1.6 in density was accompanied by a simultaneous decrease by a factor of about 1.4 in the volume reduction ratios; below 1,000 psi, the increase in density by a factor of 1.3 led to a decrease in the reduction ratio by a factor of 1.2.

The data suggest that the average decrease in volume to be expected at pressures above 2,000 psi is likely to be about 14:1 for loose household refuse of densities in the vicinity of about 6.8 pounds per cubic foot and about 9.3:1 for loose refuse of a density of about 10.8 pounds per cubic foot.

The observed relationship between the loose densities and the reduction in volume suggest strongly that the main difference between different refuse samples of residential wastes is that some samples contain a larger proportion of voids than others. However, since the increase in density, was not always accompanied by a corresponding increase in bale volume it is clear that the material properties of the refuse also affect the reduction in volume, but to a lesser degree.

Based on the data given in Table 20, it is expected that a 100 percent increase in density of the loose refuse may be accompanied by a decrease in bale volume of about 70 to 90 percent.

c) Changes in Volume and Bale Formation During Final Compaction

The changes in volume during the final stage of compaction were found to be, in all cases, much smaller than in the early stages of compaction. During the early stages which utilized only the first and second low pressure rams, the reduction in volume,

however, did not lead to the production of a stable bale structure. Similarly, the reduction in volume accomplished during the last stage by the movement of the third high pressure ram usually did not produce cohesive bales below 1,000 psi.

The most effective pressure range for the formation of cohesive bales was usually above 1,000 psi; furthermore, the stability of the bales was enhanced as the pressure increased.

In view of the importance of the final volume decrease during which the materials in the refuse are brought together into close contact, the relationships between volume decrease of different samples as a function of applied pressure were evaluated.

The change in volume during final compaction of four 25-cubic foot refuse loads of different loose densities in the pressure range of 500 to 3,450 psi are shown in Figure 10.

The results presented in Figure 10 show that the final volume obtained at about 3,500 psi differs for the two sets of refuse loads each of which occupied initially 25 cubic feet, and that the initial density had a marked effect on the ultimately achieved volume reduction. Refuse samples of loose densities of 10.2 and 11.2 (curves 1 and 2) produced larger bales than refuse samples of loose densities of 5.2 and 5.4 (curves 3 and 4); (curve 3) the volume-pressure curves of samples of initially similar densities coincided at high pressures but showed differences at lower pressures. In addition, both low and high density samples produced steeper and shallower curves, indicating inherent differences in refuse properties other than the void space in the refuse. The volume decrease in the pressure range between 1,000 and 3,500 psi was about 1.1 to 1.3 that of the volume of the samples at 1,000 psi. In comparison, the volume of the initial loads decreased by a factor of 8.0 to about 14.0 during compaction up to 1,000 psi. This demonstrates clearly that compaction in the higher pressure region does not lead to a large decrease in volume. Its value lies in the fact that a very close contact between the solids in the refuse improves the stability of the compacted refuse.

The curves in Figure 10 show that close contact between the solids was achieved for different samples at different pressures: Nearly all voids were already expelled from the refuse sample (4) at about 2,000 psi, whereas a pressure of about 3,000 psi was needed to reduce the volume of the other samples to achieve a similar result.

As mentioned before, the stability of the individual compacted bales was found to be improved after compaction at higher pressures. However, an improvement in stability was also found if the

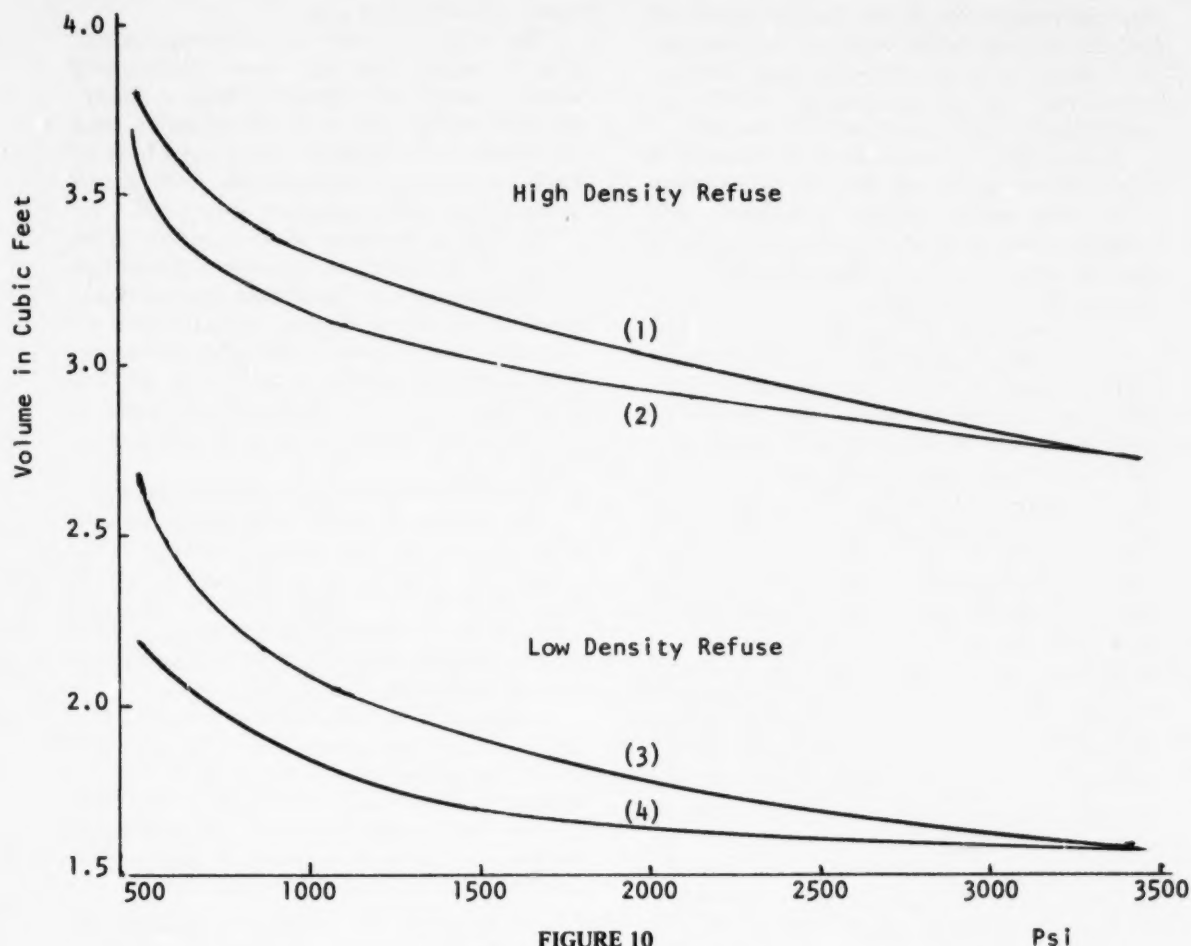


FIGURE 10
Volume-Pressure Relationship for High
and Low Density Refuse

pressure to the bale was held over a longer period of time. Increase in pressure or increase in time of pressure application led to a decrease in bale volume during compaction, and to a reduction in expansion forces after compaction.

d) Effect of Springback Forces and Pressure Holding Time on Bale Volume During Compaction

A series of experiments was made to study the effect of pressure holding time on the properties of compacted bales. This was done to determine whether holding of pressure can be used to reduce the internal expansion forces created in the bales during compaction and whether time could be used as a substitute for higher pressures.

It was found that holding of pressure during compaction always led to a decrease in bale volume. This observation indicated clearly that the internal

expansion forces created in the refuse during compaction can be partially overcome by applying pressure for a longer time. This effect indicated that the refuse behaved as a semi-elastic material. The main refuse components responsible for its over-all springback characteristics were most likely paper products. Papers, which are made up of fibers, tend to spring back after release of applied pressure if the fibers are only bent during pressure application. Higher pressures or application of pressure for a longer time, however, can weaken the bonds in the bent fibers and, therefore, reduce the springback force.

The large expansion forces created in the bales during compaction can be observed immediately after removal of the pressure from the compacted bale. Due to the operation of the compaction press used in the tests, the pressure was removed initially from the

third high pressure ram. At this time the second and first rams were still locked in position and, therefore, the expansion occurred only in the height direction. Subsequently, the bale expanded also in the other two directions, after release of the other two rams.

To determine the magnitude of the expansion in height, recordings of the ram extension-pressure curves taken during different experiments were evaluated. It was found that expansions in height of about 20 percent occurred in many cases within 1 or 2 seconds after pressure release.

A demonstration of the high expansion forces produced in the compacted bales of residential wastes is given in Figure 11. It shows a sequence of third ram deflections for a bale of refuse initially compacted at 3,500 psi and then three times at lower pressures. In this experiment the high pressure ram was retracted to its original zero position after each pressure application. The calculated height of the bale at 3,500 psi (curve "a") was found to be 12.25 inches. After release of pressure, it was found that the bale height increased by about 30 percent (see origin of curve "b"). Pressure had to be applied again to decrease the volume of the expanded bale. Even after a pressure of 1,150 psi was exerted three successive times (curves "b", "c" and "d") to the bale originally compacted at 3,500 psi, the bale height did not decrease to the value attained during the first compaction. This experiment shows that the internal pressure developed at 3,500 psi was greater than 1,150 psi. However, it also shows that the successive application of pressure led to a decrease in subsequent expansion (compare origin of "a", "b", "c" and "d").

The effect of pressure holding time on bale volume is shown in Figure 12. It can be seen that holding of pressure was quite successful in overcoming part of the counterforces initially developed in the bales. Curve "a" shows the decrease in bale height with time of a bale compacted successively at increasing pressures for 5 minutes. Curve "b" shows the results obtained with six different refuse samples prepared from the same refuse load. The smooth curve, up to about 2000 psi, represents the change in bale height of two fast runs. Holding of pressure for either 5 or 10 minutes at about 1,000, 1,500 and 2,000 psi led to the same pronounced decrease in bale volume. Curve "c" shows the decrease in bale height at about 1,000 psi with time of pressure application, and the subsequent decrease after raising the pressure to about 3,500 psi. The latter result indicates that the reduction in volume with time at low pressures is not of the same magnitude as that which can be achieved at the

highest pressures in fast runs.

The results obtained with residential wastes, loose or sacked, and also those obtained with synthetic samples of residential wastes, all showed that the maximum decrease in bale volume with time was achieved at low pressures. In the region of about 1,000 psi and up to approximately 1,700 psi the decrease in bale height was usually about 1 inch.

In addition, evaluation of the recordings of the changes in ram deflection with time indicated that the maximum decrease was reached after less than 1 minute of pressure application. This means that the optimum volume decrease in the baler can be most likely achieved by applying pressure for about 15 to 30 seconds and that the effectiveness with respect to the volume change is highest in the low pressure region.

e) Bale Densities During High Pressure Compaction

The result of the reduction in volume achieved by compaction is an increase in the density of the compacted refuse. This increase is directly proportional to the volume decrease. Since the volume decrease, with increase in pressure, is more rapid at pressures below 1,000 psi, the density also increases more rapidly in this pressure region.

The densities of the refuse gathered by the first and second ram into a space of about 7.8 cubic feet before final compaction ranged from about 12 to 50 pounds per cubic foot, a variation of about 400 percent. The average density of the 204 refuse samples was, at this stage, about 29 pounds. This includes both wet and dry refuse loads.

The densities of the compacted household refuse during final compaction, computed for samples subjected to different pressures, are presented in Table 21.

The results in Table 21 show that the average density of the compacted bales of household refuse was about 90 to 93 pounds per cubic foot at pressures above 1,850 and up to 3,500 psi. The differences in the densities of individual bales in this pressure region were found to be about $\pm$ percent of the average density.

Generally, lower values were obtained after compaction at lower pressures. However, similar values were found in different pressure regions.

An important result shown in Table 21 is the apparent lack of effect of the density of the incoming refuse on the ultimately achievable density of the compacted bale. This result seems to be in accordance with the previously made observation (see section b) that on the average, the density of the loose refuse varied primarily as a result of differences in void space within the refuse. It also implies that both wet

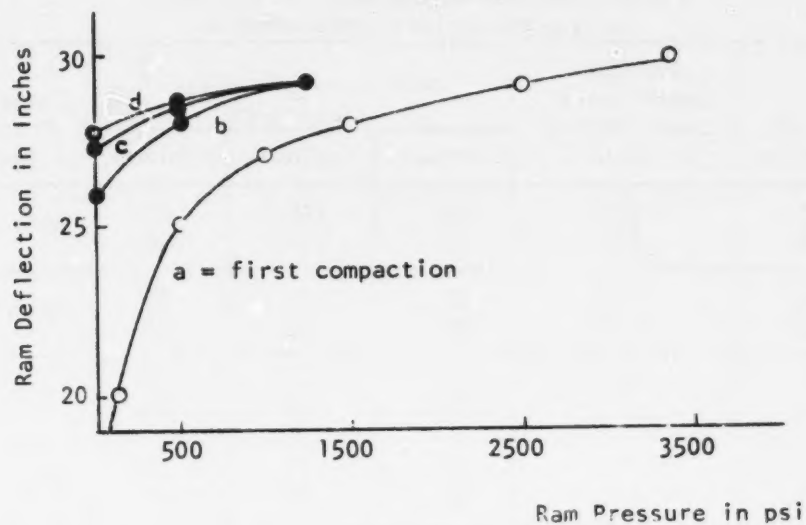


FIGURE 11
Residential Waste. Sequence of Ram Deflections for
Loose Refuse Compacted Initially Up to 3500 psi (a)
and then at 1150 psi (b, c, d)

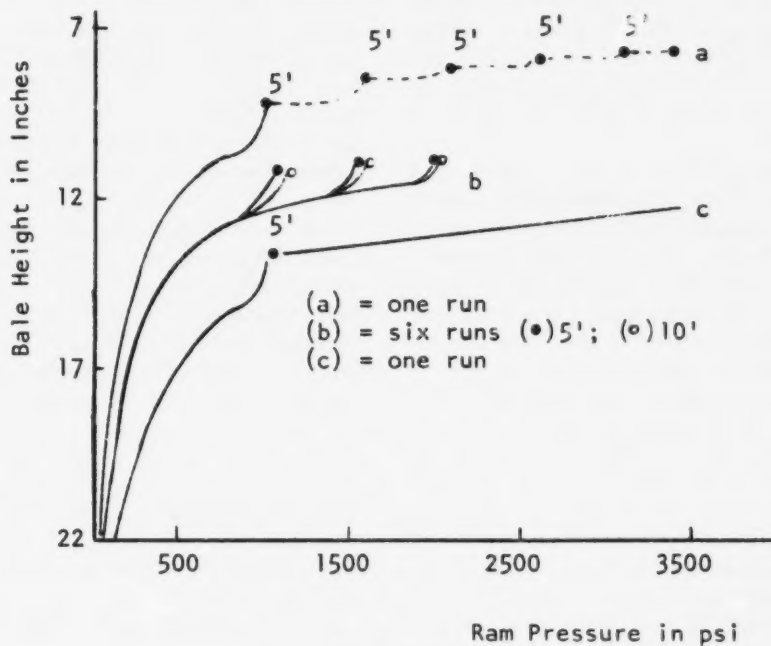


FIGURE 12
Residential Wastes. Effect of Pressure
Holding Time on Bale Height

TABLE 21
Densities of Bales of Residential Refuse, as a Function of
Incoming Densities and Compaction Pressure

No. of Samples	Average Densities of Loose Refuse (lbs/cuft)	Densities of Bales (lbs/cuft)			Compaction Pressure (psi)
		Average	Maximum	Minimum	
31 29	6.7 10.8	93 93	108 102	78 78	3000 - 3500
14 28	6.9 10.8	90 90	104 103	82 84	1850 - 2500
3 5	6.8 10.6	82 86	86 95	77 83	1350 - 1500
8 13	7.6 10.0	74 74	77 90	70 66	650 - 1000

and dry refuse loads contained either solid constituents of higher and lower densities in similar proportions, or that the proportion of one or a few constituents was so predominant in each compacted mixture that the over-all density was not appreciably affected by the introduction of moisture or items of very different densities. Since the main constituents of the household refuse received during the present program were usually paper products, it is likely that their presence in large quantities was responsible for the relatively uniform distribution of densities of different samples.

The densities of 78 pounds per cubic foot and 108 pounds per cubic foot, obtained for samples compacted at high pressures, suggest that the portion made up of items other than papers contain primarily higher density items than dry papers. This conclusion is based on the fact that the densities of different types of papers lie between 43 and 71 pounds per cubic foot, therefore, the density of a mixture of papers and similar density materials should not exceed a value of 71 pounds per cubic foot. On the other hand, higher density components, and also wet paper products should lead to a higher over-all density.

It was originally expected that compaction of very wet refuse would produce bales of appreciably higher densities than those found. However, experiments conducted with paper-water mixtures (see Section II) showed that the difference in densities between paper mixtures containing about 10 and 50 weight percent of water was not more than about 20 pounds per cubic foot. This was due to the

partial release of moisture during compaction and also to the swelling of very wet papers which therefore occupied a larger volume than dry papers.

As mentioned before, variations in the incoming densities of different refuse loads had little effect on the density of the compacted bales. These variations, however, did have an appreciable effect on the volume reduction ratio. As a result, refuse samples of the same volume produced bales of a large variety of sizes, whereas samples of the same weight produced bales of similar sizes. This finding suggests that control of the weight of the incoming refuse provides a better means for the control of the compacted bale size.

In order to determine the relationship between weight input and size of the bales, the volumes initially obtained for refuse loads of different weights were recalculated to reflect constant loads of 200 pounds. The results (Table 22) show that the average volume occupied by 200 pounds of residential wastes was about 2.04 cubic feet at high pressure and that the variations in volume were approximately ± 15 percent of the average volume. This means that 100 pounds of loose refuse produced bales of about 1.02 cubic feet on the average. The experimentally determined relationship found between incoming loose weight, compaction volume and bale density at high pressure was:

$$100 \text{ lbs} = 1.02 \pm 15\%/\text{cuft} = 93 \pm 15\% \text{ lbs/cuft}$$

On the basis of the results presented in Table 22 it would be expected that the average densities of the bales should have been about 98 pounds per cubic

TABLE 22
Volume of Bales Compacted at 3000 to 3500 Psi
for loads of 200 Pounds Loose Refuse

No. of Samples	Weight of Loose Refuse (lbs)	Volume in Compaction Chamber (cuft)			Compaction Pressure (psi)
		Maximum	Minimum	Average	
60	200	2.3	1.8	2.04	3000 - 3500

foot. However, the measured densities were found to be lower, indicating that weight losses occurred during compaction.

f) Weight Losses During Compaction

In most cases it was found that the weight of the bales, measured after removal from the press, was less than the weight of the loose charge placed in the baler.

The loss in weight was in part due to spillage of loosely adhering solids from the bale, and to loss of material which remained in the small openings between the moving parts of the press. However, these losses accounted only in part for the difference in incoming and outgoing weight of the refuse.

Weight losses which occurred during compaction arose mainly from liquid and liquid-solid suspension losses. These losses were always highest when the loose refuse was very wet. Weight losses of up to 37 weight percent were recorded for refuse exposed to rain. Moderately wet refuse usually lost only 1 to 3 percent of its initial weight. Liquid losses do not occur during compaction of dry refuse.

The average weight loss of about 5 percent in the density values (see previous section) was larger than the loss expected to occur during compaction. However, it has to be remembered that an appreciable number of bales compacted during the testing program contained liquids in excess of the liquids usually introduced by households. Some of the wet loose refuse was exposed to rain and snow, other contained moist yard rakings. Since the density values were obtained from samples ranging from very wet to very dry and since most samples were either moist or wet, a relatively high loss was recorded, reflecting the seasonal influences of winter and early spring.

The gathering and disposal of the extracted liquid has to be considered in the design of a compaction station. Uncontrolled seepage of leachings around the press and their disposal could introduce pollution hazards which have to be avoided. However, in order to identify the measures required to control this condition, it is necessary to evaluate the pollution properties of the leachings.

g) Properties of Leachings Released During Compaction

An attempt was made to obtain information of the chemical and microbiological properties of the leachings released during compaction. For this purpose a tray was installed below the compaction area of the press and the leachings were collected and later analyzed.

Leachings were collected for the chemical analysis over a period of about two weeks, since the released amounts were quite small at the time of collection. It should be emphasized that appreciable amounts of leachings are only to be expected if the refuse is wet, which was not the case for most samples compacted at the time in question. About 2.0 liters of the collected leachings were submitted for analysis.

The collection of leachings for the microbiological analysis had to be carried out in a few hours to avoid changes in properties induced by time, and to allow analysis of some of the constituents within a few hours of collection. In order to obtain a large enough sample in such a short period, water was added to the refuse before compaction. A sample of about 1.5 liters was ultimately obtained.

Precautions were taken to keep the leachings for the microbiological analysis at low temperatures during collection and transport to the laboratory by immersing the collection bottles in ice. Arrangements were made to carry out part of the microbiological analysis the same day of collection, immediately on arrival of the samples.

The chemical analyses were undertaken by the analytical personnel of the City of Chicago Testing and Inspection Division. The microbiological analyses were carried out by the personnel of the City of Chicago Board of Health. The results submitted by these two laboratories are given in Tables 23 and 24.

The chemical analysis of two different samples was made after separating each sample into two portions, one containing the liquid and the other the sludge portion of the sampler. However, the liquid portion also contained suspended solids.

The color of the sludge was light gray, and the color of the liquid was greenish in appearance. The odor of both samples was quite offensive.

The results in Table 23 show that both samples contained the same types of constituents. However, the concentrations of the individual constituents varied with the sample.

The main difference in composition of the sludge of the two samples was that Sample 1 contained a higher percentage of all constituents with the exception of organic matter. Nevertheless, in both cases the main portion of the sludge was organic. The concentration of organic matter in the liquid portion of the samples was also higher in Sample 2 than in Sample 1.

The high percentage of organic matter found in the sludge is to be expected since refuse contains a large proportion of organic constituents. It could have contained cellulose from the paper products, and other organics from different manufactured and natural products, especially those found in food and garden wastes.

The inorganic constituents of the sludge—silica, aluminum, calcium, magnesium, and iron—are likely to have been introduced through soil, vacuum cleaner catch, crushed glasses, and ceramics. The percentage of these constituents in soil and dirt is about 59 percent SiO_2 ; 15 percent Al_2O_3 ; 5 percent CaO and 3 percent Fe_2O_3 . A mixture of these types of products could readily account for the respective percentages of the individual components found in the chemical analysis. It is, therefore, unlikely that they present any pollution hazard. Only traces of sulphates and no carbonates were found in the sludge. However, an appreciable amount of phosphates was detected in both samples.

The liquid portions of the two samples were found to be distinctly different with respect to their pH. Sample 1 was slightly alkaline; Sample 2 was, on the other hand, acidic. A different sample submitted at a later stage for analysis to the Board of Health had a pH of 7, indicating that the leaching in this case was neutral.

The acid sample contained a higher proportion of

TABLE 23
Chemical Analysis of Leachings

SLUDGE	Sample 1	Sample 2
Organic Matter	38.9%	76.7%
Silica as SiO_2	30.8	6.9
Aluminum as Al_2O_3	15.2	5.8
Phosphates as P_2O_5	8.9	4.4
Calcium as CaO	2.0	1.3
Magnesium as MgO	1.4	0.0
Iron as Fe_2O_3	0.5	0.6
Sulphates as SO_3	Trace	Trace
Carbonates as CO_2	0.0	0.0
LIQUID		
pH	7.8	4.5
Total dissolved solids	6090 ppm	6040 ppm
Organic Matter	1720	4480
Bicarbonates	90	610
Sulphates	250	200
Chlorides	21	218
Heavy metals (suspension)	Large % amount	Small % amount

bicarbonates and chlorides than the alkaline sample. The bicarbonate content of the acidic sample appears, however, to be higher than would be expected for an acid solution of the given strength. Normally, carbonates are expelled out of the liquid in the form of CO_2 when subjected to relatively weak acids.

As found with the sludge, the liquid portion of Sample 2 contained a higher amount of organic matter and a smaller amount of suspended metallics than the liquid portion of Sample 1. The amount of the total dissolved solids was about the same in both cases; the amount was relatively high. It has to be remembered, however, that the samples submitted for analysis were concentrated solutions of high sludge content collected over a longer period of time.

The microbiological findings presented in Table 24 show that no pathogenic microorganisms, with the exception of one virus, were detected in the leachings. This is not surprising since many pathogens cannot survive outside a living host organism for any length of time.

Most of the identified bacteria were found to be bacterial spores. Since it is commonly recognized that bacterial spores are more resistant in their capacity to withstand external destruction, it is not surprising that they are part of the population of microorganisms found in refuse.

The aerobic and anaerobic plate counts indicate that both aerobes and anaerobes were present in about equal numbers. Their numbers were quite high. The coliform group and fecal strep counts were also high. Since a fecal coliform test was not run, it is not clear whether the strep count can be used as an adequate indicator of fecal contamination.

It is not surprising that the leachings contained an appreciable amount of some of the pollutants, especially since both the chemical and biological tests were carried out with concentrated samples designed primarily to allow detection of the type of pollutants which could be encountered in the refuse. It should also be remembered that the investigation was restricted to a few tests and that a more quantitative study would be required to assess the pollution potential of the leachings. The findings, however, show the promise of the approach and the great desirability of an expanded systematic program which would be to the benefit of the whole solid-waste disposal field.

With respect to compaction, however, it has to be emphasized that the chemical and microbiological constituents detected in the leachate were not introduced into the refuse by the compaction process. These constituents are part of the normal makeup of solid wastes disposed of in everyday

operations. Since some of the pollutants are extracted from the wastes during compaction, the compacted wastes should, in fact, contain fewer contaminants than the wastes entering the compaction plant.

h) Volume Expansion of Bales After Compaction

The volume of each compacted refuse sample was found to increase immediately after removal of the compaction pressure. Initially, the expansion inside the baler occurred only in the height direction since the two lower pressure rams were locked into position and therefore prevented expansion into the length and width direction. It was, however, quite apparent that a three-dimensional expansion of the bale would have occurred if the freedom of expansion had not been restricted. In fact, it was found necessary to unlock the low pressure rams and allow a three-dimensional expansion in order to remove the bales from the compaction chamber without destruction. Nevertheless, the expansion in height was always more pronounced than in the other directions.

The expansion of the bales outside the compaction chamber was measured at predetermined time intervals. The rate of increase was found to be largest, in all cases, immediately after compaction was completed. However, the bale volume increased at a slower rate over a long period.

Measurements taken 1 to 2 minutes after completion of compaction showed that the volume expansion during that time amounted to about 50 to 60 percent of the original compacted volume. The computed values of the volume expansion occurring during 1 to 2 minutes for samples compacted at different pressures in fast runs (without holding of pressure) are given in Table 25.

The average volume increase of the samples of lower loose densities was slightly higher than the volume increase of the higher density samples. However, large variations in volume expansions were recorded for individual samples.

An accurate determination of the volume of the expanded bales was not possible. The expansion forces acting within the bale were found to be non-uniform. This non-uniformity led to the formation of distorted bales and prevented accurate volume determinations. The distortion of the bales was always highest for those compacted at lower pressures. The least distortion occurred after compaction at about 3,500 psi. An improvement was also found for bales compacted at lower pressures, if the pressure was applied for a period of time.

As a rule the expansion in volume within 1 to 2 minutes after release of pressure from the bale was in the region indicated in Table 25. Variations in volume expansion of the different bales were in the range of

TABLE 24
Microbiological Analysis of Leachings

A. <u>BACTERIOLOGY</u>	
Aerobic plate count	8.3×10^6 organisms/ml.
Anaerobic plate count	7.7×10^6 organisms/ml.
Identified Bacteria (to genus)	1. <u>Bacillus</u> sp. 2. <u>Coliform</u> group 3. <u>Proteus</u> sp. 4. <u>Streptococcus</u> sp. (alpha hemolytic and non-hemolytic noted.) 5. <u>Alcaligenes</u> sp. 6. <u>Micrococcus</u> sp. (coagulase negative) 7. <u>Flavobacter</u> sp. 8. <u>Aerobacter</u> sp.
Yeasts	Yeast cells were observed.
Molds	1. <u>Penicillium</u> 2. <u>Streptomyces</u> 3. <u>Paecilomyces</u> 4. <u>Mucor</u>
B. <u>PARASITOLOGY</u>	A number of free living amoebae as well as ciliates were noted.
C. <u>WATER BACTERIOLOGY</u>	
1. Standard plate count @ 35°C:	4.9×10^7 organisms/ml.
2. MPN technique:	9.2×10^8 organisms per 100 ml.
3. Fecal streptococci (membrane filter):	7.0×10^6 organisms per 100 ml.
4. Staphylococci (membrane filter):	5.7×10^7 organisms per 100 ml.
D. <u>VIROLOGY</u>	Virus isolated and identified as ECHO by anti-serum neutralization.
E. <u>CHEMISTRY</u>	pH: 7; D.O.: none

Bales made from refuse containing snow developed an ice cover which inhibited bale growth within the first expansion period. The expansion of these bales was usually not more than 25 volume percent. High values, however, were obtained for individual samples of both very dry and very wet refuse. The high values probably resulted from the high springback forces of bent paper fibers when dry, and also from swelling effects of paper materials when wet.

The expansion of bales occurred preferentially. In all cases the expansion of bales compacted at high pressures was substantially greater in the direction of the bale height. For example, for a bale whose over-all volume increased about 60 percent, the height increased by about 50 percent, and the length and width about 4 and 2 percent, respectively. As a rule the expansion in length was greater than in width.

The preferential expansion of the bales followed the sequence of the three-step compaction process: least expansion occurred in the direction of the lowest pressure application, first ram movement; and the maximum expansion occurred in the direction of the highest pressure, third ram movement.

The respective order of expansion in the three pressure directions remained always the same, irrespective of the properties of the compacted refuse. However, if the refuse was wet or if the refuse was compacted at lower pressures, the degree of the expansion in width and length was higher. The maximum increase after 1 or 2 minutes was about 20 percent in length and about 10 percent in width.

The volume of bales after 24 to 72 hours was always larger than after the first few minutes. Bales stored individually and left to expand without any restriction, grew up to 95 percent larger than their original compacted volume.

The computed volume reduction ratios after volume expansions are also given in Table 25. The effect of loose densities on the volume reduction ratios found for the refuse during compaction (see Table 20) was found to be present after volume expansion. The variations in volume reduction ratios ranged between 5.1 and 6.4 for high density samples and between 6.6 and 10.0 for the low density samples.

Placement of bales into close proximity, next to each other and on top of each other, could reduce the over-all growth either in one or all directions depending on the stacking procedure adopted. However, additional work is needed before a definite assessment can be made of the influence of stacking on bale growth.

i) Densities of Bales After Volume Expansion

The direct consequence of the expansion of the bales is a reduction in the densities of the bales. The densities of the bales after initial expansion are given in Table 26.

It can be seen that the average densities of the bales compacted at 3,000 to 3,500 psi were about 61 to 65.5 pounds per cubic foot after expansion took place. These values are found to be about 30 percent lower than the values obtained during compaction (Fig. 13). The maximum decrease in density (about 37 percent) appeared to occur with bales compacted at 1,350 to 1,500 psi.

TABLE 25
Volume Expansion of Bales After Compaction

No. of Samples	Average Loose Densities (lbs/cuft)	Average Volume % Increase after 1 to 2 Min.	Volume Reduction Ratios after 1 to 2 Min.	Compaction Pressure (psi)
31 29	6.7 10.8	50% 43	10.0 : 1 6.4 : 1	3000 - 3500
14 28	6.9 10.8	66% 56	7.9 : 1 6.1 : 1	1850 - 2500
3 5	6.8 10.6	62% 51	7.4 : 1 5.5 : 1	1350 - 1500
8 13	7.6 10.0	49% 59	6.6 : 1 5.1 : 1	650 - 1000

The data in Table 26 show a distinction between the densities of bales compacted above and below 1,850 psi. The density values of the bales compacted above 1,850 are all close to 60 pounds per cubic foot, whereas those below that pressure have values close to 50 pounds per cubic foot. The differences between the densities of the samples of initially high and low loose densities is found to be slight.

j) Effect of Pressure, Pressure Holding Time and Moisture Content on the Stability of Bales After Compaction

Several factors were found to affect the stability of the compacted bales of residential wastes. The major factors were compaction pressure, time of pressure application, and the moisture content of the wastes.

TABLE 26
Densities of Bales after Volume Expansion

No. of Samples	Average Densities of Loose Refuse (lbs/cuft)	Average Densities of Bales After 1 to 2 Min. Volume Expansion (lbs/cuft)	Compaction Pressure (psi)
31 29	6.7 10.8	61 65.5	3000 - 3500
14 28	6.9 10.8	58.5 60.0	1850 - 2500
3 5	6.8 10.6	50 54	1350 - 1500
8 13	7.6 10.0	49.5 48.0	850 - 1000

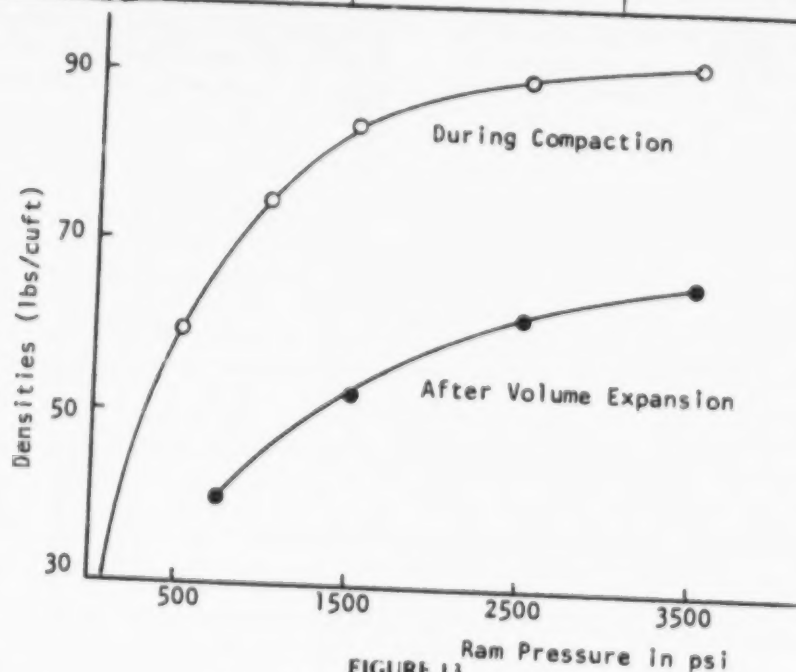


FIGURE 13
Average Densities of Residential Wastes
During and After Compaction

In the absence of excessive moisture, compaction at high pressures resulted in the formation of stable bales. On the other hand, bales compacted at low pressures were quite fragile.

Fragile bales were usually obtained after compaction at pressures between about 500 to 1,000 psi. These bales occasionally fell apart immediately after removal from the baler. Some fell apart after being handled successively several times. An improvement in stability was found for bales compacted at pressures between 1,000 and 1,500 p.s.i. However, the stability of most bales was markedly improved after compaction at 2,000 psi and up to 3,500 psi. A further increase in pressure, up to 6,000 psi, produced no apparent improvement in bale stability.

The over-all stability of the bales compacted at about 1,000 and 1,500 psi usually improved appreciably if the force on the bales was held for several minutes (see Part "d"). The bales compacted at about 1,000 psi for 5 minutes seemed to be stable as those compacted at 1,500 to 1,750 psi without holding of pressure. Similarly, the bales compacted at

about 1,500 psi for 5 minutes appeared to have the properties of samples compacted at about 2,000 psi without holding of pressure.

The stability of bales of very high moisture content was always poor, irrespective of the compaction pressure applied. There were, however, indications that the stability of the bales containing an appreciable amount of moisture could be improved if the compaction pressure were lowered.

2. Paper-sacked and Plastic-sacked Residential Wastes

The composition, moisture content, and densities of the uncompacted paper- and plastic-sacked refuse were discussed previously (see Section Two). The over-all properties of the refuse inside the sacks were similar to those of the loosely delivered refuse, the main difference being that moisture content of the refuse in the sacks remained largely unaffected by external influences such as rain and snow. This meant that the adverse effects, introduced into the loose refuse by rain, were eliminated. The only other significant difference between the sacked and loose refuse was the presence of the sack itself. The

TABLE 27
Volume Reduction Ratios of Paper- and Plastic Sacked
Residential Wastes During Compaction

Densities of the Uncompacted Refuse (lbs/cuft)			Volume Reduction Ratios			Compaction Pressure (psi)
Maximum	Minimum	Average	Maximum	Minimum	Average	
10.1	4.8	7.4	17 : 1	9 : 1	13 : 1	3300 - 3500
9.7	6.3	7.7	13 : 1	9 : 1	11 : 1	1850 - 2000

TABLE 28
Densities of Bales of Paper- and Plastic Sacked Refuse
During Compaction

Densities of the Uncompacted Refuse (lbs/cuft)			Densities of Bales (lbs/cuft)			Compaction Pressure (psi)
Maximum	Minimum	Average	Maximum	Minimum	Average	
10.1	4.8	7.4	106	90	94	3300 - 3500
9.7	6.3	7.7	93	81	85	1850 - 2000
Precompacted at 3500 psi		69.75	70	69	69.5	6000*

* 2 bales only

compaction results and the effect of the enclosure are discussed below.

a) Volume Reduction During Compaction

The over-all change in volume of sacked refuse with compaction pressure followed the same pattern as described in the compaction of the loose refuse (see parts a, b, c, and d under Residential Refuse-Loose). Most of the reduction in volume took place at pressures below 1,000 psi. Above 1,000 and up to 3,500 psi, the volume decreased continually but at a lesser rate.

The values obtained for the volume reduction ratios of sacked household refuse were similar to those of loose residential wastes. The computed averages for the sacked refuse compacted at about 3,400 and 1,900 psi were about 13:1 and 11:1 respectively, as shown in Table 27.

The relationship between the loose densities and the volume reduction ratio was the same as that found for the loose refuse. That is, the reduction in volume was always greater (17:1) when the density of the uncompacted sacked refuse was lowest (4.8 lbs/cuft).

The presence of sacks had no apparent effect on the reduction in volume.

b) Bale Densities During Compaction

The densities of sacked refuse, during compaction, were found to be of the same order of magnitude as those of the loose residential wastes. The computed values of the densities of 30 samples of sacked refuse are given in Table 28.

As with loose residential wastes, the densities of different sacked refuse samples were found to be independent of the densities of the incoming refuse. Furthermore, the average densities, and also the maxima and minima, were close to those obtained for loose refuse.

The values obtained by compaction of precompact sacked refuse from 3,500 to 6,000 psi show that the high pressure did not increase the density of the bales. Similar results were obtained with other samples precompact at 3,500 psi.

c) Volume Expansion and Bale Densities After Compaction

As with all other types of mixtures of household wastes, the volume of the compacted sacked refuse did not remain the same after removal of the compaction pressure. The volume increase was again found to be more rapid immediately after pressure release. The increase in volumes and the associated decrease in bale densities during an initial expansion of 1 to 2 minutes are shown in Table 29.

The volume reduction ratio of the bales compacted at about 3,500 psi decreased within 1 to 2 minutes after removal of pressure by about 31 percent of its original value. Simultaneously, the bale density decreased from 94 to 64 pounds per cubic foot. The average volume increase for bales compacted at about 3,400 psi was 47 percent. The average volume increase for bales compacted at about 2,000 psi was nearly 10 percent less. Nevertheless, the volume of the bales compacted at lower pressures was always larger after expansion than the volume of bales compacted at the higher pressures.

d) Effect of Adhesives on Volume Reduction Ratios and Bale Densities During and After Compaction

Several adhesive experiments were carried out with samples of 10 bags of paper-sacked refuse. In each case the adhesive was sprayed on the outside of the sacks immediately before compaction. The results obtained with samples sprayed with a cellulose type of adhesive containing about 20 percent of solids dissolved in water are given in Table 30.

As expected, the presence of adhesives had no

TABLE 29
Volume Reduction Ratios and Bale Densities of Paper Sacked
Residential Wastes During and after Compaction

Volume Reduction Ratios (averages)		Average Volume Increase %	Densities of Bales (lbs/cuft, averages)		Compaction Pressure (psi)
During Compaction	After 1 to 2 Min. Volume Expansion		During Compaction	After 1 to 2 Min. Volume Expansion	
13 : 1	9 : 1	47	94	64	3300 - 3500
11 : 1	8 : 1	38	85	63	1850 - 2000

TABLE 30
Effect of Adhesives on Bale Densities and Volume Reduction
Ratios for Paper Sacked Household Refuse Compacted at
Different Pressures

No. of Samples	Densities of Loose Refuse (lbs/cuft) (averages)	Densities of Bales (lbs/cuft, averages)		Volume Reduction Ratios (averages)		Maximum Compaction Pressure (psi)
		During Compaction	After Springback 1 to 2 Min.	Loose/Compaction Chamber	Loose/Springback 1 to 2 Min.	
5	6.5	86	66	14 : 1	10 : 1	3300 - 3500
3	6.6	80	54	12 : 1	8 : 1	1850 - 2000

effect on the compaction properties of the wastes during compaction. The effect of the adhesive on volume expansion during the first two minutes was slight.

Initially, the volume of the compacted bales increased nearly as rapidly as the volume of the sacked refuse which was not sprayed. This was probably due to the presence of an appreciable amount of moisture in the diluted adhesive which decreased the immediate effectiveness of the adhesive. The expansion of bales compacted at about 3,400 psi was about 8 percent less than the expansion of the unsprayed bales. The main difference between the sprayed and unsprayed bales, however, was found to be in the appearance and stability of the bales after standing. The sprayed bales were less distorted and more rugged than those not sprayed.

e) Effect of Pressure Holding Time, and Refuse Properties on the Stability of Bales of Sacked Refuse

The stability and appearance of the paper-sacked bales compacted in normal fast runs at about 2,000 and up to about 3,500 psi was very good. The stability of bales compacted in fast runs at about 1,500 psi was acceptable. An improvement in stability always resulted if the pressure to the bale was applied for an extended time. Very stable bales were produced by the addition of adhesives to the outside of the paper sacks.

The stability and appearance of the compacted plastic-sacked refuse was, as a rule, poor. The plastic sacks tended to burst and adhered very poorly to each other. Addition of adhesives to the outside of the plastics appears to be essential for the compaction of this type of sacked refuse.

The absence of excessive moisture (exclusion of rain) proved to be a great asset in the compaction of the paper-sacked refuse. It introduced very favorable conditions with respect to the subsequent stability of the compacted refuse. In addition, the paper sacks remained largely intact during compaction. This improved the appearance of the bales and also prevented spillage of loosely adhering refuse components from the outside of the bales.

It can be concluded, therefore, that paper-sacked refuse, if compared to loose refuse, has distinct advantages with respect to its compaction properties.

3. Shredded Residential Wastes

Only one truckload of shredded residential wastes, received from Madison, Wisconsin, was investigated in the present study.

The wastes (see Section Two) contained a high proportion of paper products. The loose densities of the individual samples varied only between 8.2 and 11.0 pounds per cubic foot. This is not surprising since all refuse samples came from the same load. The average moisture content, 10.7 percent by weight, was low; it was comparable to that of dry household refuse delivered either loose or sacked.

The relatively high densities of the incoming shredded refuse, and its uniformity, were undoubtedly the result of the processing which reduced the void space and provided some mixing. The loose refuse had the appearance of shredded newspapers.

a) Volume Reduction During Compaction

The volume reduction ratios of the shredded wastes compressed at different pressures are given in Table 31. In addition, the table includes results of the reduction in volume of two samples to which water was added, and also the results of two samples which were compacted for 5 minutes each at the indicated pressure.

The results show that the volume of the shredded wastes decreased appreciably during compaction. The average volume reduction ratio of the wastes compacted at about 3,400 psi in fast runs was of the order of 10 to 1. This result indicates clearly that, although some reduction in void space was achieved by shredding, a large amount of air was still trapped in the refuse.

As with other types of wastes, a further reduction in volume resulted when the pressure to the bales was held for several minutes. The results obtained with the samples to which water was added show very clearly that moisture affects the compaction properties of wastes. The volume of the wet bales was larger than the volume of the dry bales, and as a result the volume reduction ratio decreased.

The increase in bale size of the wet bales suggests that the absorbed water caused swelling of the papers in the shredded refuse, which as a result occupied a larger volume than it would have in the absence of excessive moisture. The swelling properties of papers are most likely the cause of the partial proportionality found between the volume reduction ratio and the density of the incoming refuse (see parts b and c, Residential Wastes-Loose).

b) Bale Densities During High Pressure Compaction

The average densities of the shredded samples were, as a rule, several pounds higher than the average densities of the sacked and loose wastes compacted at the same pressure. This, however, does not necessarily mean that the packing of the waste components in the refuse bales was denser, although such an

interpretation is possible.

Calculations showed that weight losses due to liquid extraction were similar for shredded and dry loose residential wastes. In addition, loose residential wastes, containing a similar low moisture content as the shredded refuse, often produced bales of similar densities.

The computed densities of the bales, during compaction, are given in Table 32.

c) Volume Expansion of Bales and Bale Densities After Compaction

The increases in volume and the associated decreases in volume reduction ratios and densities of compacted shredded refuse are shown in Table 33.

The results show that the expansion in volume was highest for bales to which water was added. The total moisture content of these bales was probably close to 22 percent (a) and 28 percent (b) of the total weight (see Section Two: Moisture in Shredded Refuse). These wet samples lost up to about 7 pounds in weight during compaction.

The wet refuse bales expanded about 40 percent in height and about 20 percent in length. Similar results were also obtained with unshredded wet household refuse.

The expansion of the non-wetted refuse compacted at 3,400 psi was on the average about 31 percent in height, 4 percent in length and 3 percent in width. Similar results were also obtained with the paper-sacked and relatively dry loose refuse.

The increase in volume of the two bales compacted for 5 minutes at 1,850 and 3,400 psi was

TABLE 31
Volume Reduction Ratios of Different Sample of Shredded Refuse

No. of Samples	Average Densities of Loose Refuse (lbs/cuft)	Volume Reduction Ratios During Compaction (averages)	Compaction Pressure (psi)	Comments
24	9.4	10.7 : 1	3400	Normal fast runs
1	8.3	12.1 : 1	3400	5 Min. pressure holding time
1	10.2	9.9 : 1	3400	Water added: 11% by wt.
1	10.9	9.2 : 1	3400	Water added: 17% by wt.
8	10.2	9.4 : 1	1850	Normal fast runs
1	9.9	10.1 : 1	1850	5 Min. pressure holding time
1	9.9	6.9 : 1	350	Normal fast run

TABLE 32
Densities of Bales of Shredded Refuse During Compaction

No. of Samples	Average Densities of Loose Refuse (lbs/cuft)	Densities of Bales (lbs/cuft)			Compaction Pressure (psi)	Comments
		Maximum	Minimum	Average		
24	9.4	103	96	101	3400	Normal fast runs
1	8.3	-	-	99	3400	5 Min. pressure holding time
1	10.2	-	-	98	3400	Water added: 11% by wt.
1	10.9	-	-	98	3400	Water added: 17% by wt.
8	10.2	100	92	95	1850	Normal fast runs
1	9.9	-	-	98	1850	5 Min. pressure holding time
1	9.9	-	-	66	350	Normal fast runs

TABLE 33
Volume Reduction Ratios and Bale Densities of Shredded Refuse During and After Compaction

No. of Samples	Volume Reduction Ratios (averages)		Volume Expansion after 1 to 2 Min. %	Densities of Bales (lbs/cuft, averages)		Compaction Pressure (psi)
	During Compaction	After 1 to 2 Min. Volume Expansion		During Compaction	After 1 to 2 Min. Volume Expansion	
24	10.7 : 1	7.4 : 1	44	101	68.6	3400
1	12.1 : 1	8.5 : 1	42	99	69.7	3400 (5')
1 (a)	9.9 : 1	5.7 : 1	73	98	56.0	3400 (H ₂ O)
1 (b)	9.2 : 1	5.1 : 1	80	98	55.0	3400 (H ₂ O)
8	9.4 : 1	6.7 : 1	45	95	67.3	1850
1	10.1 : 1	7.0 : 1	44	98	68.0	1850 (5')
1	6.8 : 1	3.5 : 1	93	66	34.0	350

about the same as that of the average expansion of the bales compacted at the same pressures for a fraction of the time.

The largest increase in volume, 93 percent occurred after compaction of the refuse at about 350 psi. In this case the bale expanded primarily in the length direction by about 40 percent, and about 26 and 9 percent respectively in the direction of height and width. The bale produced was quite soft and spongy and its stability was poor.

After the initial growth, the increase in volume of the bales proceeded at a slower rate. A representative example of the increase in bale volume during 24 hours is given in Table 34 for two shredded refuse bales compacted in fast runs at 3,400 and 1,850 psi, respectively.

Holding of pressure on the bale for 5 minutes resulted in the formation of a very compact structure which appeared to be more stable than those subjected to the same pressure for a very short time. However, additional information is needed to assess the influence of holding time on volume expansion after compaction of shredded refuse.

The appearance of the bales of low moisture content was superior to that of the bales of the same moisture content produced by compacting loose household refuse. It was also better than the appearance of the paper-sacked refuse bales, which was very good.

In conclusion, it should be pointed out that the investigation was carried out with a single load of shredded refuse of high paper and low moisture

TABLE 34
Volume Increase of Compacted Shredded Refuse With Time

Sample	Time (minutes)	Volume Increase (%)	Compaction Pressure (psi)
1	1	44	3400
	5	49	
	30	58	
	1440	71	
2	1	60	1850
	5	69	
	30	82	
	1440	95	

The results given in Table 34 show that the total increase in volume after 24 hours was about 71 and 95 per cent. It should be remembered, however, that the values given represent the increase in volume of bales which were allowed to expand freely in all directions. As mentioned previously, the degree of volume expansion of bales confined into a given space and piled on top of each other is likely to be less than that found for bales allowed to grow unrestricted.

The densities of the shredded refuse bales, after expansion, were approximately the same as other refuse bales of high densities.

d) Effect of Pressure, Moisture Content, and Pressure Holding Time on Bale Stability

The stability of the shredded refuse compacted at 1,850 and 3,400 psi was very good. The bales produced from the dry refuse had straight sides and sharp edges. The only bale which had poor stability was the one which was produced at 350 psi. The wet bales tended to bulge.

content, and that additional work is needed to evaluate fully the effect of shredding on compaction.

4. Gas Development in Residential Waste Bales

To obtain information about the gaseous decomposition products of compacted residential waste bales, several gas samples were taken and analyzed.

The bales were prepared from truck refuse containing a large proportion of yard cleanings. The composition of this refuse is given in Table 10.

Six bales were prepared in total. Each bale contained 200 pounds of the refuse. However, two samples were compacted after filling of the refuse in paper sacks, whereas the other four were made from the loose refuse. In addition, three samples were compacted at about 2,000 psi and three at about 3,500 psi.

Two bales containing loose residential wastes and two bales containing paper-sacked residential wastes were stored as they came out of the press. The

TABLE 35
Gas Analysis and Bale Temperature of Compacted
Spring Cleaning Residential Wastes

Bales	Time of* Sampling (days)	% of Gas				Bale Temperature (°F)	
		CO ₂	O ₂	CO	CH ₄	Inside	Surface
Residential - Loose (3500 psi)	4.5	7.0	13.1	0.009	none	105	95
	8	2.9	17.5	trace	none	102	93
Residential - Loose (2000 psi)	4.5	6.4	14.2	0.011	none	129	125
	8	7.3	12.4	trace	none	105	119
Papersacked (3500 psi)	4.5	4.2 ¹	16.2	0.013	none	118	113
	8	4.5	15.6	trace	none	100	110
Papersacked (2000 psi)	4.5	-	-	-	-	115	103
	8	6.9	13.2	trace	none	115	103
Plastic covered (3500 psi)	4.5	3.5	17.3	0.019	none	106	98
	8	3.7	16.7	trace	none	106	90
Plastic covered (2000 psi)	4.5	7.6	12.4	0.013	none	97	93
	8	4.7	15.5	trace	none	92	89

* Time elapsed after bale was made.

(1) Mean value of both papersacked samples.

remaining two bales of loose residential wastes were tightly wrapped in plastic sheeting and then stored.

The hut in which the bales were stored was kept at a temperature of about $85 \pm 5^{\circ}$ F.

After 1 day of storage, the two samples wrapped in plastic were found to be warm to the touch. In addition, droplets of water had started to develop on the inside of the plastic cover. The samples not wrapped in plastic remained cool and dry to the touch.

After 3 days of storage, all samples were covered in plastic to allow accumulation of the gaseous products. Within 24 hours those not wrapped previously also released a large amount of moisture and were warm to the touch.

On the fourth day of storage gas samples were taken from each bale by insertion of a rubber tubing inside the cover. Subsequently, a second set of gas samples was taken from the bales which, after 8 days of storage, were still in their plastic cover.

The analysis of the gases was made by the Peoples Gas, Light and Coke Company, Chicago, Illinois. The results of the gas analyses and measurements of the bale temperature taken at the

time of gas sampling are given in Table 35.

The results of the gas analysis (Beckman, Chromatography, and Infrared) show that the collected gases did not contain methane (CH₄) and that the main decomposition product was carbon dioxide (CO₂). This, together with the observation of the large amount of water formed on the inside of the plastic wrapping of all bales, indicates strongly that the bacterial activity was aerobic.

The temperature of the bales, taken at the time of gas sampling, was found to be the highest for the bale of loose residential wastes compacted at 2,000 psi and wrapped in plastic 24 hours before sampling. On the other hand, the temperature was lowest for the bale compacted at the same pressure and containing the same loose refuse, which was, however, wrapped in plastic immediately after compaction.

The results of the gas analysis and temperature seem to indicate that the decomposition of organics was more vigorous in bales compacted at 2,000 psi than in the other bales. This might have been due to the fact that these bales contained more air and that its diffusion through the bale was facilitated by the looser compaction.

III. COMPACTION OF SYNTHETIC REFUSE SAMPLES

Several series of experiments were carried out with samples which were specially prepared for testing purposes. The composition and the properties of the uncompacted synthetic samples used in the investigation are described in Section Two.

The procedure adopted for compaction was the same as that used in the compaction of the residential wastes delivered from households. The samples were subjected to compaction in the same press (Fig. 3) and the applied pressure and the change in volume was measured electronically as described before (see Section I).

The results of this part of the experimental study, which was designed to investigate in more detail the compaction properties of residential wastes and other refuse components of interest, are given in the following sections.

1. Synthetic Refuse Mixtures—Loose

Two types of refuse mixtures were prepared, both representing dry city household refuse of high paper content.

Each mixture contained about 60 weight percent of mixed paper products and 40 weight percent of other components which included metals, glass and ceramics, food wastes, liquids, construction wastes, plastics, textiles, rubber, leather, and dirt. The types and respective percentages of the individual paper products and other components are given in Table 15.

The moisture content of mixtures 1 and 2 was estimated to be about 19 and 14 weight per cent, respectively (see Section Two, Moisture Content of Synthetic Waste Mixtures).

Several samples of the same composition were used to investigate the effect of compaction variables on bale formation and bale properties. Eighteen samples of synthetic loose refuse were subjected to compaction. Six samples contained Mixture 1 and 12 samples contained Mixture 2.

a) Effect of Pressure on Bale Volume During Compaction

As with other refuse samples, the refuse was first gathered by the first and second ram into a space of about 7.8 cubic feet. The refuse was then compacted by the third high compression ram. During the final operation the decrease in volume was accomplished by the reduction of the height of the bale; the other two dimensions remained unchanged. The decrease in bale height of six 200-pound samples (three samples of each mixture) compacted at about 1,500, 2,000 and 3,500 psi respectively, is shown in Figure 14.

It can be seen that the reduction in volume of all samples started at about 150 psi. The decrease in volume up to about 300 psi was nearly the same for samples of both mixtures. However, above 300 psi the volume of the samples made up from Mixture 1 was usually lower than the volume of the samples made up from Mixture 2.

The difference in volume reduction between the samples of the two different mixtures was slight. However, the results reflect the sensitivity of compaction to composition. Mixture 1, which contained more moisture, compacted to a higher degree than the drier, but otherwise similar, Mixture 2.

Compaction at about 3,500 psi reduced the original volume (7.8 cu ft) by about 69 per cent (a) and 67 per cent (b).

Mixture 2 were about 7.6 and 8.0 pounds per cubic foot, respectively. However, the computed volume reduction ratios of the two types of samples were similar to those obtained with residential wastes of higher loose densities.

The average volume reduction ratios of different samples compacted at different pressures are given in Table 36.

b) Effect of Pressure Holding Time on Bale Volume During Compaction

The effect produced by applying pressure to the bale (Mixture 2) for a length of time is shown in Figure 15.

The decrease in bale height at about 850 to 1,000 and 1,500 psi was, after holding of pressure, nearly equivalent to the decrease which was achieved by compaction in normal fast runs (Fig. 3 curve) at a 700 psi higher pressure. At about 2,000 to 2,500 psi the decrease with time was nearly equivalent to that obtained in a fast run at about 500 psi higher pressure. Increase in pressure holding time from 5 to 10 minutes had no effect.

The examination of the various recordings taken during the above runs, and for other refuse samples to which pressure was applied for a period of time, showed that the decrease in volume shown in Figure 15 was achieved in less than one minute.

c) Volume Expansion of Bales After Compaction

The increase in volume of the compacted bales of both mixtures was followed after removal from the press over a period of 24 hours. Measurements were taken after 1, 5, and 30 minutes and then after 24 hours. The increase in volume within the first minute was found to be usually more than 50 percent of the increase after 24 hours.

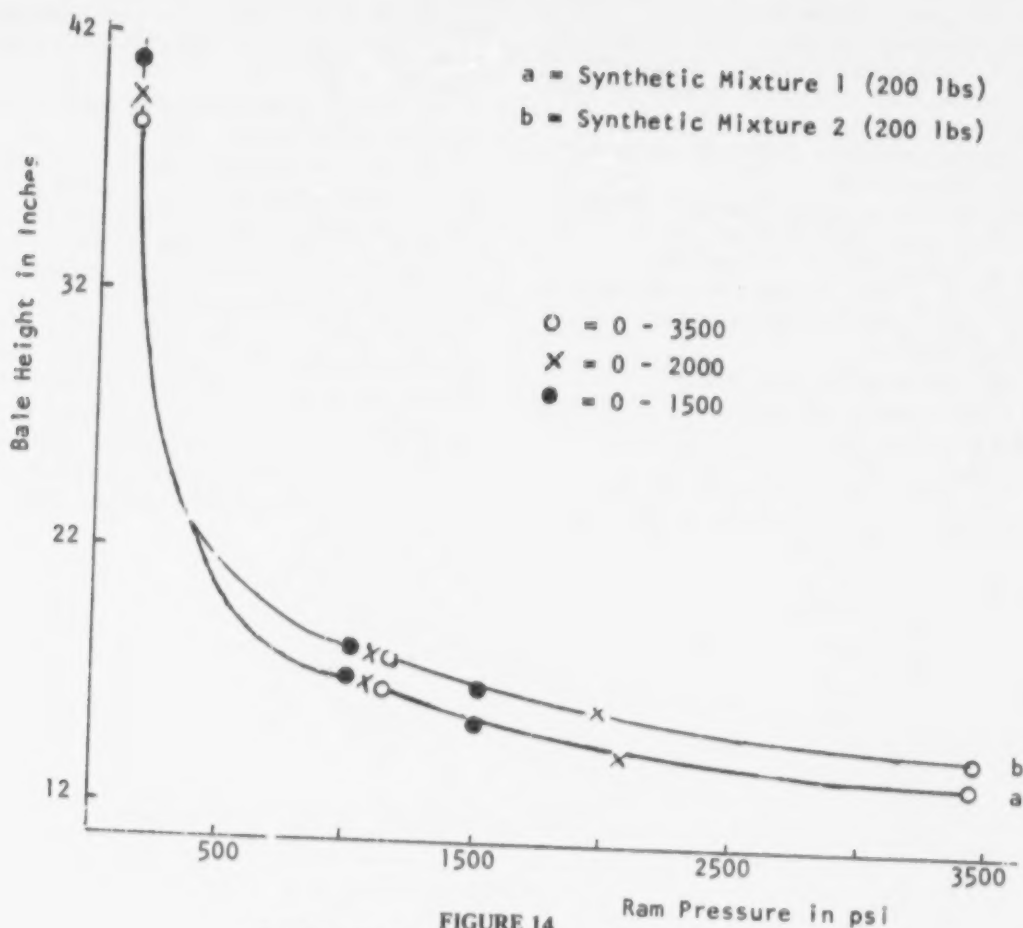


FIGURE 14
Synthetic Refuse—Loose. Decrease in Bale Height
as a Function of Pressure.

TABLE 36
Average Volume Reduction Ratios of
Synthetic Refuse Mixtures

Volume Reduction Ratios (averages)		Compaction Pressure (psi)
Mixture 1	Mixture 2	
10.0 : 1	9.0 : 1	3500
9.0 : 1	7.8 : 1	2000
8.8 : 1	7.5 : 1	1500
8.1 : 1	6.9 : 1	1000

The increase in volume was found to be related to the compaction conditions. Bales compacted at higher pressures expanded less than those compacted at lower pressures. The volume increase of bales compacted at the same pressure was found to be lower if the compaction pressure on the bales was held for several minutes.

The average percentage increase in volume of 200-pound bales of both mixtures, compacted in fast runs at 1,500, 2,000 and 3,500 psi (full lines), and the increase of bales compacted 5 to 10 minutes at about 1,000, 1,500 and 2,000 psi (dashed lines), is shown in Figure 16.

The increase in bale volume was found to be least for a bale compacted for 25 minutes at successively higher pressures from 1,000 to 3,000 psi (see Fig. 15, dotted line) and then finally at 3,500 psi.

The average values obtained for the bales compacted at 2,000 and 1,500 psi for 5 to 10

minutes were close to those of the bales at 3,500 psi. Bales compacted at 1,000 psi for 5 and 10 minutes expanded less than those compacted in fast runs at 1,500 (Fig. 16,).

The increase in pressure holding time from 5 to 10 minutes had no apparent effect.

The computed volume of nine bales compacted for 5 to 10 minutes at different pressures (Mixture 2) and the volume of the expanded bales after 1 minute and 24 hours is shown in Figure 17. The volume of three bales compacted in fast runs, after 24 hours expansion, is given for comparison (dashed line).

The stability of the synthetic refuse bales compacted in normal fast runs was comparable to the stability of high-paper-content dry residential wastes compacted at the same pressures. Bales compacted at about 2,000 psi and higher pressures were stable. Reasonably stable structures were also obtained after compaction at about 1,500 psi; however, these bales

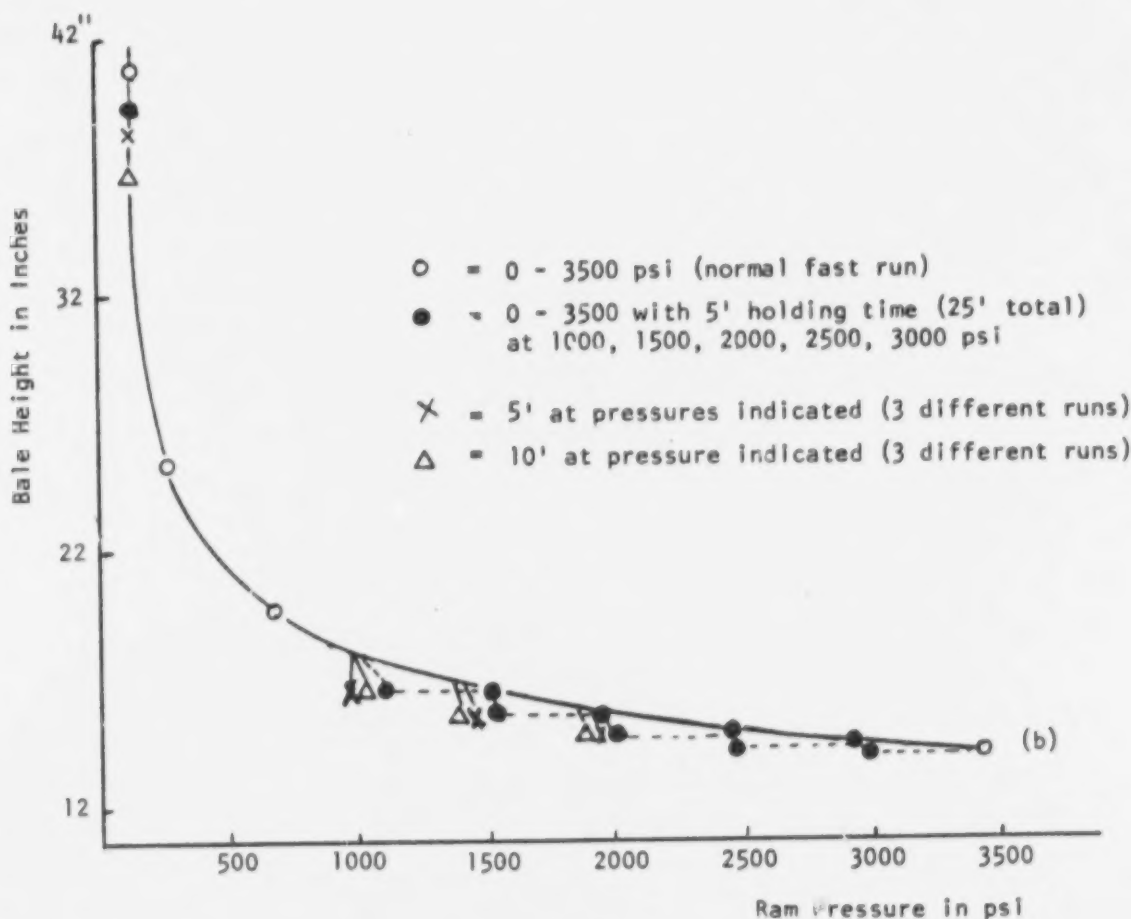


FIGURE 15
Decrease in Bale Height as a Function of Holding Time

tended to bulge. A distinct improvement in shape and compactness resulted in each case in which the bales were compacted for several minutes.

Recordings of changes in bale height with time of pressure application indicated that a maximum reduction in volume was reached after holding of pressure for less than 30 seconds. Since an equivalent decrease in volume was reached only at higher pressures in fast runs, and since an increase in pressure always improved the stability of the bales, it is likely that less than 1 minute of pressure holding time will be required to achieve the effect produced by the increase in pressure.

A comparison of the final volume (after 24 hours) of bales compacted with time and of bales compacted in fast runs at low pressures shows that an improved stability equivalent to an increase of about 750 psi in pressure was achieved by holding the pressure for 5 minutes. It is, therefore, reasonable to expect that bales compacted at about 1,000 psi for 1

minute should be as stable as those compacted at 1,500 psi in fast runs. Similarly, bales compacted for 1 minute at 1,500 and 2,000 psi should be as stable as those compacted at 2,000 and 2,500 psi in fast runs.

2. Synthetic Mixtures in Paper Sacks

A series of experiments was also made with samples of synthetic Mixtures 1 and 2, which were placed into paper sacks and then compacted. This was done since it had been found that compaction of paper-sacked refuse offered advantages over that of loose refuse. These advantages were associated with the elimination of rain from the refuse and also with the reduction in spillage of loosely adhering refuse components from the compacted bales (see Residential Wastes in Paper Sacks).

Each compaction experiment was carried out with nine bags filled with synthetic refuse. The compaction properties of the two sacked mixtures are on the following page.

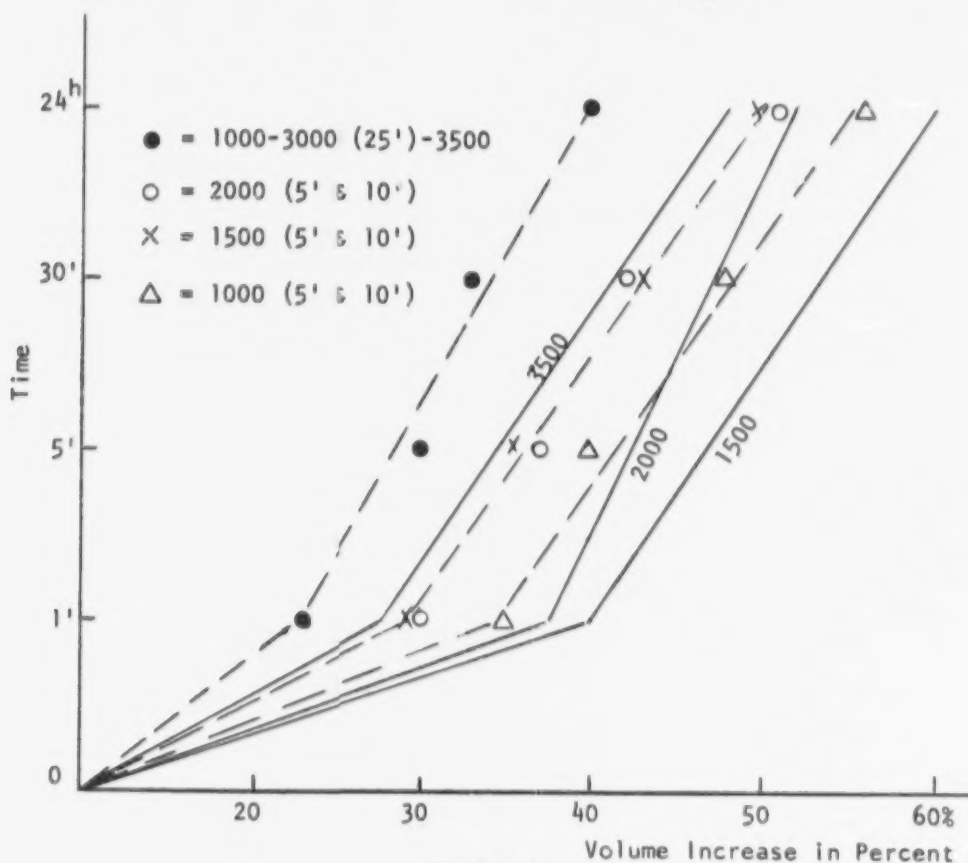


FIGURE 16
Synthetic Refuse Loose. Average Volume Increase of
Bales of Both Mixtures Compacted With and Without
Holding Pressure.

a) Effect of Pressure and Pressure Holding Time on Bale Volume During Compaction

The compaction of the paper-sacked refuse of Mixtures 1 and 2 followed the same pattern as that of the loose synthetic mixtures. As before, the volume of the bales containing Mixture 2 was slightly larger than that containing Mixture 1. However, the volume of the compacted sacked refuse seemed to be slightly larger than that of the loose refuse.

The decrease in bale height of 20 samples of 200 pounds each (Mixture 2), compacted by holding of pressure and in normal fast runs is shown in Figure 18. The dotted line represents the result of one run during which the pressure was held successively for 5 minutes at about 1,000, 1,500, 2,000, 2,500, and 3,000 psi,

The results obtained with the paper-sacked samples followed the same pattern as found with the loose wastes. The decrease in volume recorded for the samples compacted for 5 to 10 minutes was also reached after less than 1 minute of holding time.

b) Volume Expansion and Bale Stability of Paper-sacked Synthetic Refuse

The increase in volume of the compacted bales of paper-sacked refuse after release of pressure appeared to be higher by several percent than the volume increase of the baled loose synthetic refuse. However, since variations in volume expansion of individual bales of both loose and sacked refuse were found, additional work would be necessary to determine whether the observed effect is reproducible.

As with loose refuse, the average volume expansion was found to be less for bales compacted

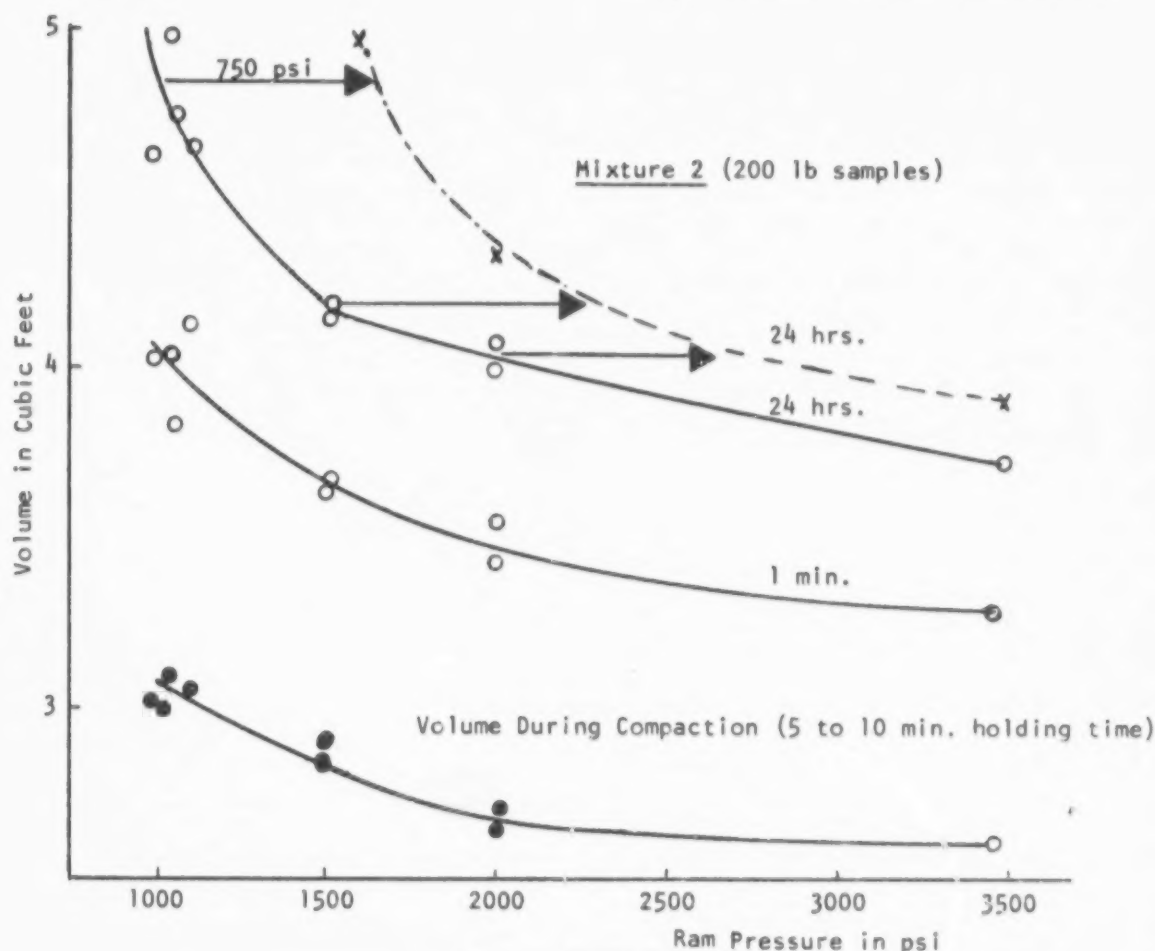


FIGURE 17
Synthetic Refuse—Loose. Volume Changes of Bales
Compacted for 5 to 10 Minutes.

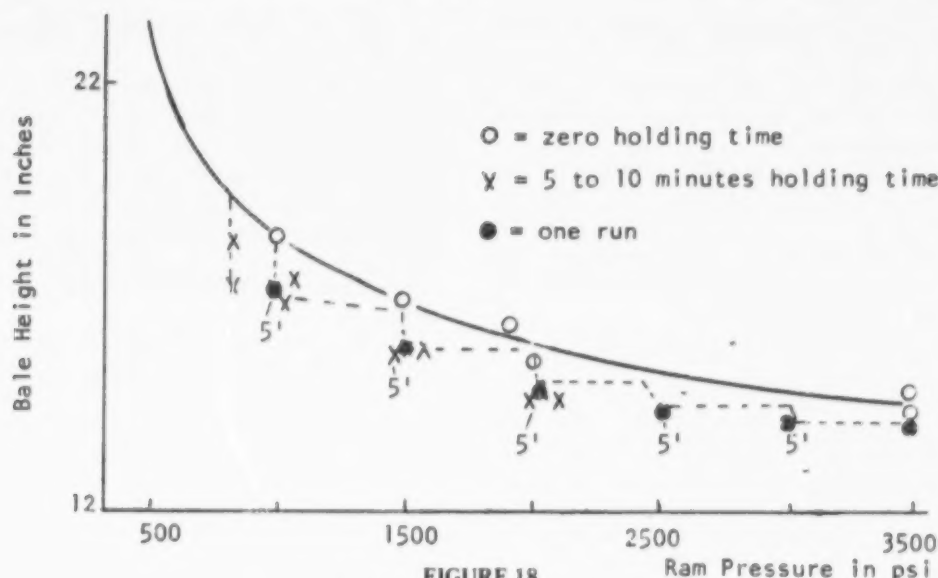


FIGURE 18
Paper-sacked Synthetic Refuse—Decrease in Bale
Height During Compaction With and Without
Holding of Pressure.

at a given pressure for several minutes. The average expansion for bales compacted at about 1,000 and 1,500 psi in fast runs and after holding of pressure for 5 and 10 minutes is given in Table 37.

The increase in bale volume of the paper-sacked synthetic refuse compacted at low pressures for several minutes was about 15 to 20 per cent less than for bales compacted in fast runs. At higher pressures, the decrease in expansion was about 6 volume per cent.

As with all refuse bales, the expansion was highest in the height direction. However, the length of the bales (second highest expansion direction) increased slightly more than the length of the bales of the loose refuse compacted at the same pressure.

The stability of the paper-sacked refuse bales was either better, or comparable to, the stability of the loose refuse bales compacted under the same conditions. The sacked bales had the appearance of a packaged bundle.

3. Synthetic Paper-Water Samples: Moisture Experiments

It was found that a small amount of moisture has a beneficial effect on the compaction of residential wastes of high paper content. In small quantities it facilitates the bending and breaking of the cellulose fibers and fosters adhesion between the papers. In very large quantities, however, it leads to the formation of paper pulps which hinder compaction.

Difficulties with respect to compaction were

TABLE 37
Volume Increase of Paper-sacked Synthetic Refuse Bales
After Compaction at Low Pressures

Compaction		Average Volume Increase (%)			
Pressure (psi)	Time (min.)	1 Minute	5 Minutes	30 Minutes	24 Hours
1000		52%	55%	74%	78%
850-1000	(5' & 10')	34	41	51	57
1500		48	55	66	71
1500-1600	(5' & 10')	30	36	41	54

experienced with waterlogged residential wastes exposed to rain. They resulted mainly from the formation of paper pulps which tended to be released with great force from the press openings during high pressure compaction.

In view of the large quantities of papers usually found in wastes, it was felt that additional information on the interaction of moisture and papers was needed to determine the quantity of water which can be accepted without impairing the compaction of residential wastes.

a) Effect of Moisture on Bale Volume During Compaction

Several series of experiments were made with samples containing: (1) paper mixtures which were predried; (2) paper mixtures which were not predried; (3) newspaper sheets not dried but separated; and (4) newspaper bundles not dried. A premeasured amount of water was added to each paper sample. The paper-water mix was then left to stand at least

overnight. (For details see Section Two: Synthetic Samples of Paper and Water.)

In order to compare the effect of different moisture contents on the compaction properties of different samples, all measured values obtained with different weight samples were computed to a standard weight per sample of 200 pounds. This weight represents the total weight of water and paper in each sample. The weight percentage of moisture in each sample was then determined and its effect was evaluated.

It was found that the height of the compacted bales, during compaction, decreased as the weight percentage of moisture was increased. In other words; the replacement of papers by moisture did result in the formation of smaller bales than were obtained with samples of the same weight which had more solids and less water. The decrease in bale height of 200-pound samples as a function of moisture content is shown in Figure 19. Calculations show that 100

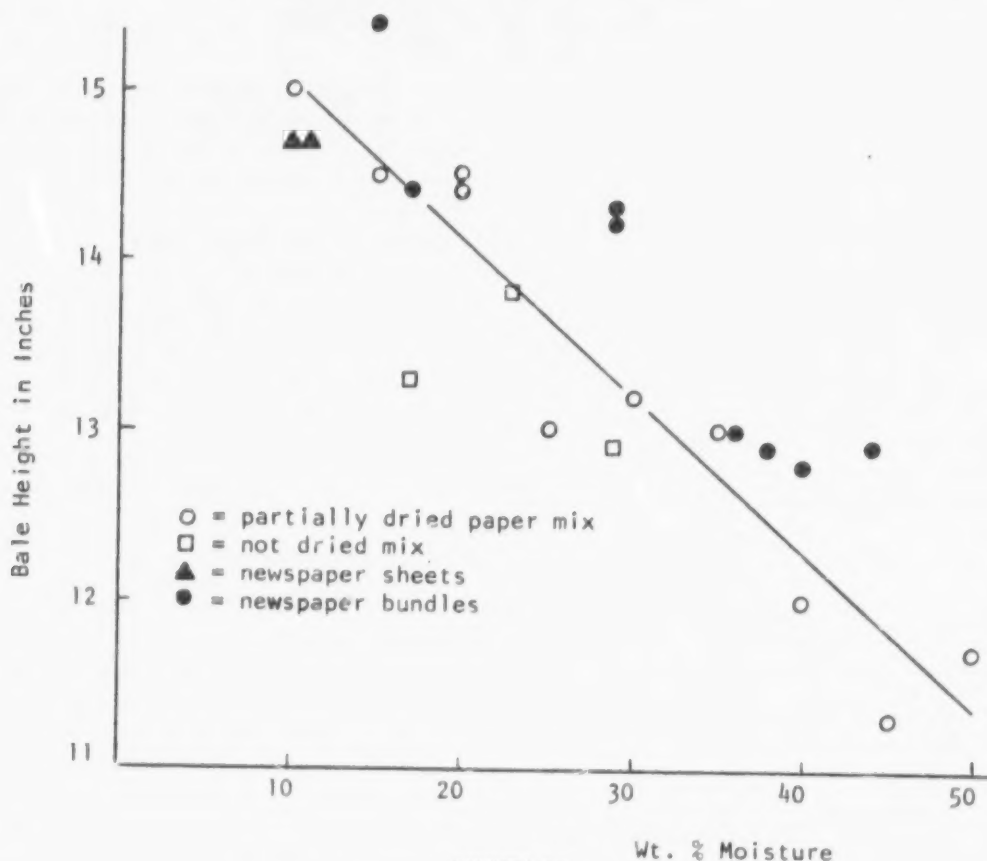


FIGURE 19
Effect of Moisture Content on Bale Height During
Compaction of Paper Samples Compacted at About 3500 psi.

pounds of water occupies less than 50 per cent of the volume occupied by 100 pounds of paper mixtures, and slightly more than 50 per cent of the volume taken up by newspapers.

The increase in density resulting from the decrease in volume of samples of equal weight was found to be about 5.0 pounds per cubic foot for an increase of about 10 weight per cent of moisture (see Figure 20).

b) Volume Expansion After Compaction As a Function of Moisture Content

The increase in volume of the compacted paper samples, after release from the press, was found to be related to the moisture content. Samples containing a larger proportion of moisture expanded more in a given time period than those containing less moisture.

A 10 percent increase in moisture of samples containing 10 to 35 weight percent of moisture usually resulted in an increase in volume of about 10 percent. Above 35 weight percent, the increase in volume was larger. Bales containing more than 40 weight percent of added water tended to disintegrate immediately after release of pressure.

The expansion of mixed paper samples, over a period of 24 hours, containing 10 to 50 weight

percent of water in addition to absorbed moisture is shown in Figure 21.

c) Stability of Different Paper-Water Samples

The stability of all paper bales which contained a very large amount of moisture was found to be poor. However, an appreciable amount of moisture was accepted by the papers without developing pulps. Most paper samples composed of 50 per cent paper and 50 per cent water were found to be unstable. In some cases, paper samples of much lower moisture content developed cleavages and slowly disintegrated.

Wetted newspaper bundles folded during compaction tended to unfold, even after an addition of about 45 percent of water. The folded paper bundles were, in this case, not sufficiently wet to allow breakage of fibers in the bends. As a result, most compacted bales of paper bundles were unstable, irrespective of the moisture content.

Separated newspapers and paper mixtures, to which up to about 35 weight percent of water was added, were reasonably stable. The actual moisture content of these and all other bales was probably about 10 percent higher since the papers contained absorbed moisture before the addition of water.

Expansion of the paper-water bales became more

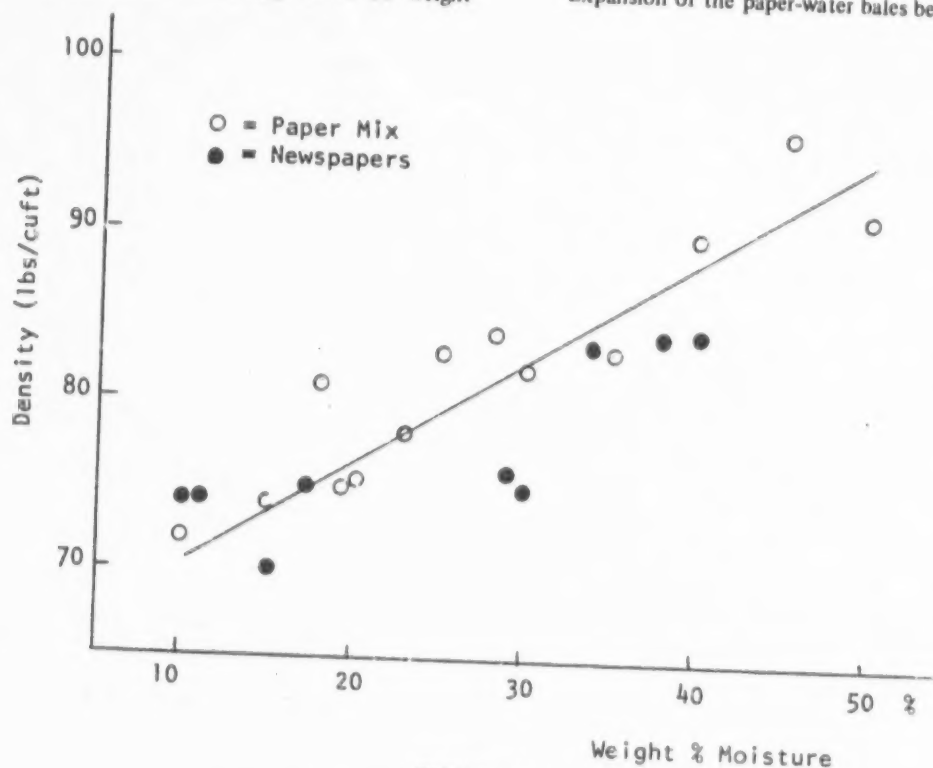


FIGURE 20
Increase in Density as a Function of Moisture Content.

three dimensional with increase in moisture content. For example, the bale containing 50 percent of water expanded after 10 minutes by about 28 percent in height and by about 26 percent in length.

Recompaction of bales which had fallen apart did not produce stable units.

4. Synthetic Samples of Papers and Adhesives

A limited series of experiments was carried out with paper mixtures to test the effect of adhesives on the volume expansion and stability of paper bales. The adhesives used are described in Section Two of this report. The effect of these adhesives on the compaction of paper-sacked refuse was discussed in the section on residential wastes.

Each paper sample was first wetted in order to raise its moisture content to about 20 weight percent. The adhesives were dissolved in water and then introduced into the mix by spraying. The paper refuse was subsequently compacted at about 3,500 psi. Four different water-soluble adhesives containing 15 percent solids were used. Both the compaction volume and the expansion volume of the different samples were found to be similar irrespective of the adhesives introduced.

The average volume increase was about:

42 percent after 1 minute,
47 percent after 5 minutes,
54 percent after 30 minutes, and
62 percent after 24 hours.

The over-all increase in volume with time was about 15 volume percent less than the volume increase of similar samples which did not contain adhesives. It is likely that a further reduction in volume expansion would have been achieved with adhesives containing less water or with initially drier refuse samples. Application of heat during compaction is also likely to be beneficial since it could reduce the moisture level and thereby improve the effectiveness of the adhesives.

Although the volume expansion after compaction was not substantially reduced by the addition of the adhesives, the paper bale stability was distinctly improved and the appearance of the bales was excellent. The work with adhesives was not pursued further because the stability of the baled household refuse was found to be quite good without the use of adhesives.

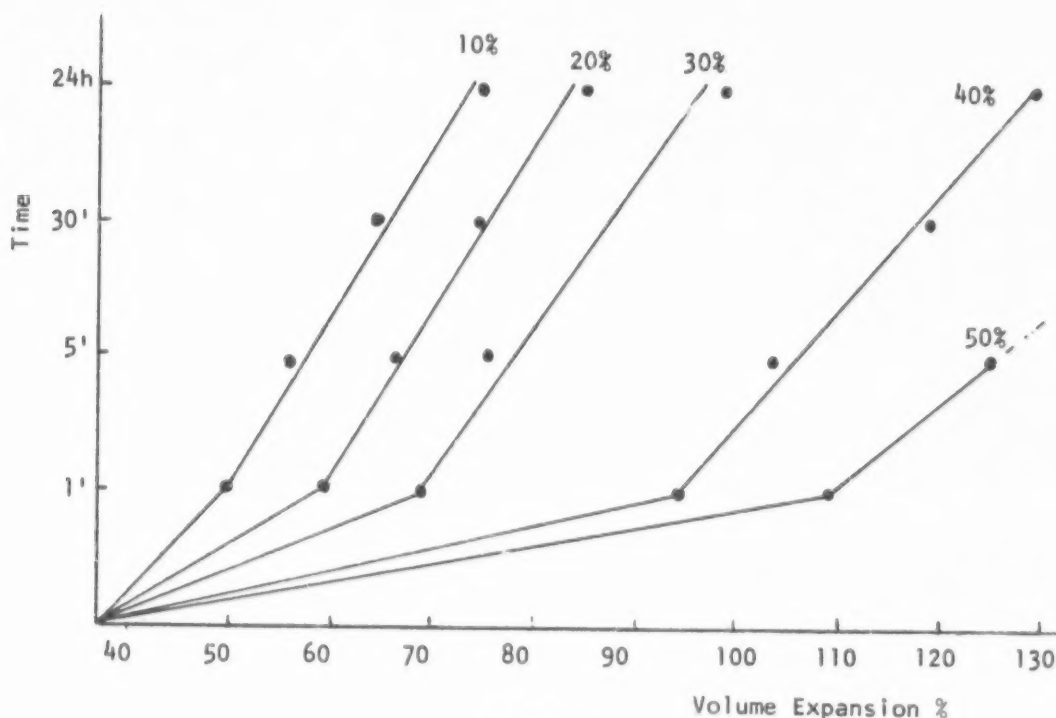


FIGURE 21
Volume Expansion of Compacted Paper Bales Containing
10 to 50 Weight Percent of Added Water

5. Compaction Properties of Selected Refuse Components

The compaction properties of individual refuse components of interest were tested, either alone or in combinations.

The properties of different refuse components compacted at about 3,500 psi are described below:

1. *Rubber Tires.* Several samples of rubber tires were subjected to compaction. However, they could not be compacted. After release of pressure the tires always separated.
2. *Rubber Tires Enclosed in Wire Mesh.* The compacted bundles of tires enclosed in the wire mesh always expanded rapidly. The wire mesh, depending on its strength, usually burst open at a few or many welded spots.
3. *Shredded Rubber and Residential Wastes.* Residential waste, containing about 25 percent of small rubber pieces, produced good bales. Shredded rubber on its own could not be compacted.
4. *Metal Cans and Oversized Metallic Wastes.* All metallic waste products, including refrigerators, washing machines, stoves, and appliances, produced excellent bales.
5. *Oversized Wastes.* Mixtures of refrigerators or other oversized metallic wastes, together with furniture and textiles produced very stable bales.
6. *Oversized Wastes and Household Refuse.* These mixtures produced very good bales.
7. *Plastic Scrap.* Compacted mixtures of plastics did not hold together after release of pressure.
8. *Very Dry Papers.* Such papers did not produce stable bales.
9. *Vegetables, Fruits, Meat Scraps.* These wastes could not be compacted on their own or in combination.
10. *Vegetables, Fruits and Residential Refuse.* An appreciable amount of food pulp was formed by compacting residential wastes which contained a large amount of fresh vegetables or fruits. Addition of about 25 weight percent of vegetables to residential wastes produced a large amount of fine pulp which was partially released from press openings already at about 900 psi. The pulp which adhered to the outside of the compacted bale fell off after removal of pressure.
11. *Cooked Meats and Residential Refuse.* Similar results as those obtained with vegetables and fruits were obtained with meats

containing a large amount of moisture.

12. *Vegetables and Wood Shavings.* The addition of vegetables to wood shavings produced unstable bales.

13. *Wood Shavings.* Wood shavings, alone, produced relatively good bales.

14. *Wood Chips and Residential Refuse.*

Mixtures of residential wastes and wood chips produced good bales.

6. Measurements of Load Distribution During Compaction of Synthetic Mixtures and Other Refuse Samples

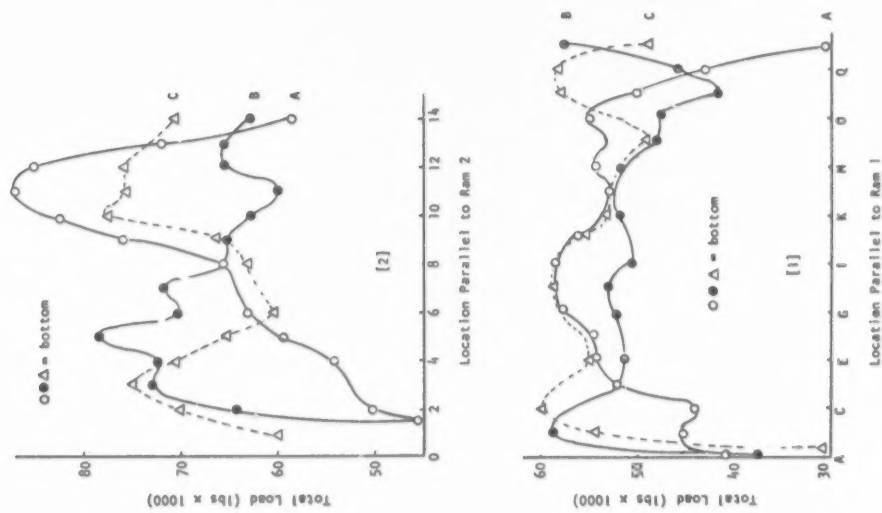
Two types of load distribution measurements were carried out using penetration gage assemblies. Initially, one penetration gage assembly was introduced into the compaction chamber adjacent to the third ram to measure load distributions at the interface between the high pressure ram and the refuse bale. Subsequently, two penetration gage assemblies were used, one next to ram three and the other adjacent to the coverplate directly opposite ram three. The latter arrangement was used to measure load losses across the bale during compaction.

The basic principle of the measuring method and the gage assemblies themselves were described previously (see Section One, 11-3). In brief, the gage contained 252 steel balls for peak force measurements. The diameters of the indentations in the measuring plate were calibrated for different applied loads. The calibration curve obtained was then used to determine the peak load of each indentation.

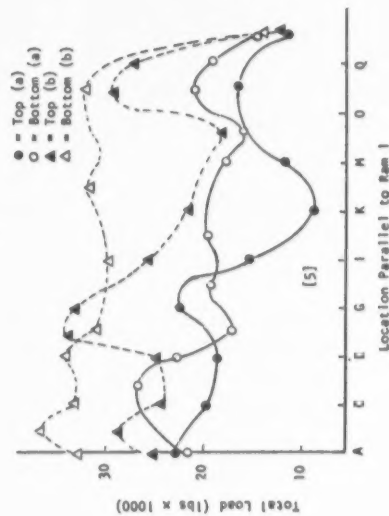
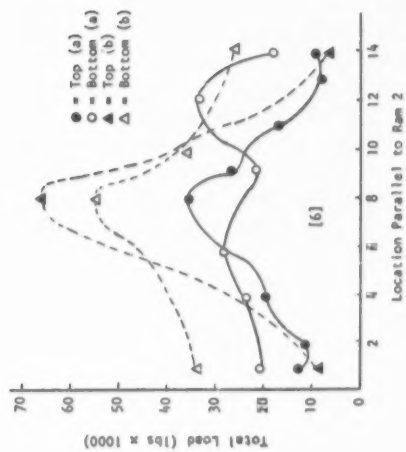
Contour drawings (not shown) were made of the load levels of the indentations produced during compaction in the bottom and top plates. The long side of the plates was marked from A to R. This side, which coincides with the 20-inch length of the bale, was parallel to the first ram of the press. The plate side perpendicular to the first ram (parallel to the second ram) of 16 inches width was marked from 1 to 14.

The loads of the individual indentations were summed along lines parallel and perpendicular to the face of ram one. The resultant total load of each row was then plotted to indicate the load distribution across the plate parallel to the first or second ram, in each case starting at the corner position of these two rams. The total load distribution at the bottom and top of the bales is shown for different samples and different compaction conditions in Figure 22.

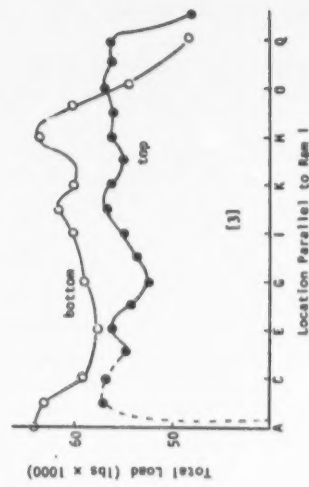
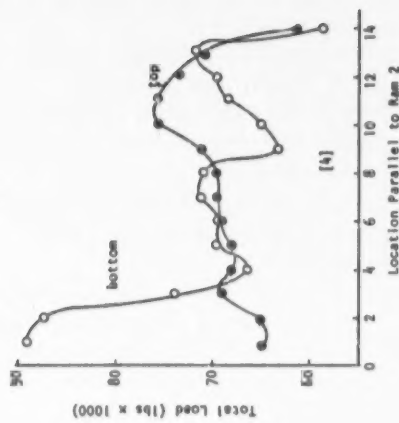
The load distribution at the bottom of the bales (adjacent to ram three) is given in Figure 22, 1 and 2, for samples containing Residential Wastes (A); Tin Cans (B); and Shredded Residential Wastes (C). These



(A) Residential, (B) Tin Cans, (C) Shredded Refuse.
Total Load Distribution of Bales Compacted at 3400 psi.



Synthetic Mixture. Total Load Distribution of
Bales Compacted at 1000 (a) and 1500 (b) psi.



Sandust. Total Load Distribution of
Bales Compacted at 3400 psi

FIGURE 22
Total Load Distribution at Bottom and Top of Bales

samples were compacted at about 3,400 psi hydraulic pressure.

The load distributions at the bottom and top of bales are shown for a synthetic sample of sawdust (Fig. 22, 3 and 4) and for two synthetic refuse mixtures in paper sacks (Fig. 22, 5 and 6). The compaction pressure used in the compaction of sawdust was about 3,400 psi and for the two synthetic mixture samples was about 1,000 psi (a) and 1,500 psi (b).

The results presented in Figure 22 show several distinct features. In most cases, the load distribution pattern was found to be more uniformly parallel to ram one than parallel to ram two. It seems, therefore, that the sweeping action of the first gathering ram and the second ram tend to introduce areas of varying densities perpendicular to the first ram face. Low load values were recorded primarily adjacent to the sides parallel to the first and second ram face (row A and row I). However, a sharp decrease in load values is also found next to the other two sides of the compaction chamber (row R and row 14).

A comparison of the load distribution patterns of the different waste samples show that sawdust produced the most uniform loading pattern of the materials tested. This is not surprising since its consistency resembled more that of a granular homogeneous substance than any of the other materials tested. The load values obtained for rows next to the first and second ram were found to be higher at the bottom than at the top of the bale. The decrease of the total load value of row A and row I at the top of the bale indicates that load losses had occurred during the high pressure compaction.

With respect to the other samples, the most uniform load distribution was always found parallel to the first ram face (see lower figures). They were also usually more uniform at the bottom face of the bales than at the top face. Pronounced load peaks

were recorded for load patterns parallel to ram two (see upper figures).

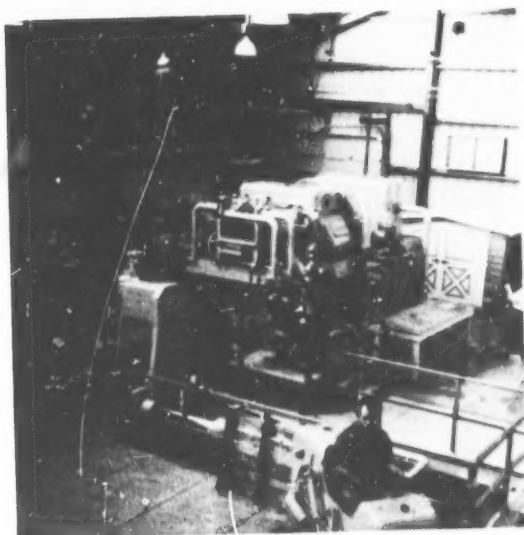
The loads next to the bottom face (Fig. 22, 1 and 2) were more evenly distributed for shredded wastes (1C and 2C) than for the residential waste (1A and 2A), and for Tin Cans (1B and 2B).

Bell-shaped curves were obtained both with residential wastes and with the simulated synthetic mixtures of residential wastes (Fig. 22, 2 and 6). It can be seen that the load distribution curves parallel to ram two show pronounced single peak maxima at the center of the bale face (synthetic mixture) or slightly off the center (residential wastes). The developed peak force is found to be especially pronounced at the top of the bale compacted at 1,500 psi (Top b, Fig. 22, 6).

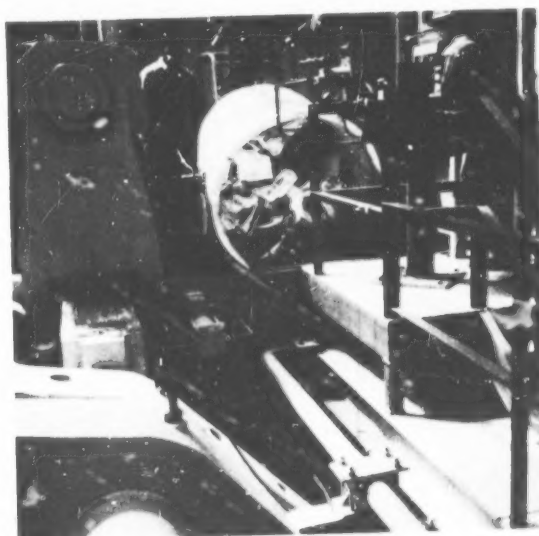
The total load transmitted to the top plate was, as a rule, less than the load experienced by the bottom plate. The load losses occurred as a result of shearing effects by which part of the applied force was lost to the side walls of the chamber (see first and last rows in Fig. 22, 3, 4, 5, and 6).

Calculations show that the over-all load loss for sawdust compacted at 2,400 psi was only about 7 percent. Higher losses were found to occur at low pressures, and with less uniform materials. The over-all loss for the paper-sacked bales, compacted at 1,500 and 1,000 psi, was about 23 percent and 27 percent, respectively.

The presented results show that peak loads can be developed both at the bottom bale face, resting on the high pressure ram, and at the top of the bale. At present it is not clear whether the peaking occurs primarily as a result of individual material properties of the bale components, or whether it is related to the compaction conditions. Further work in this direction could provide information which could be of great value in the design of compaction presses.



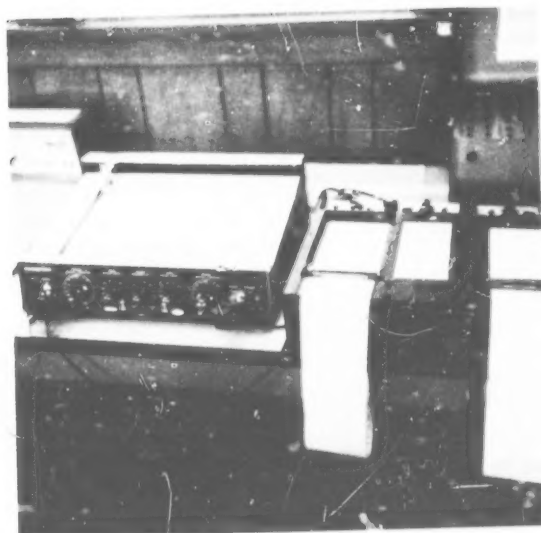
(1)



(2)



(3)



(4)

Compaction of Solid Wastes:

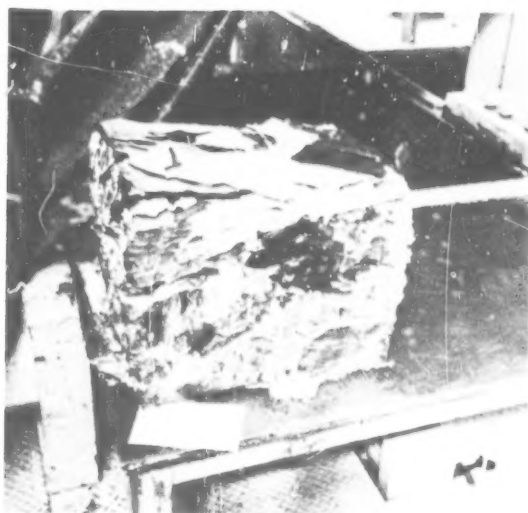
- (1) Compaction Press;
- (2) Loading of Press Charging Box;
- (3) Weighing of Compacted Bale;
- (4) Electronic Measuring Equipment.



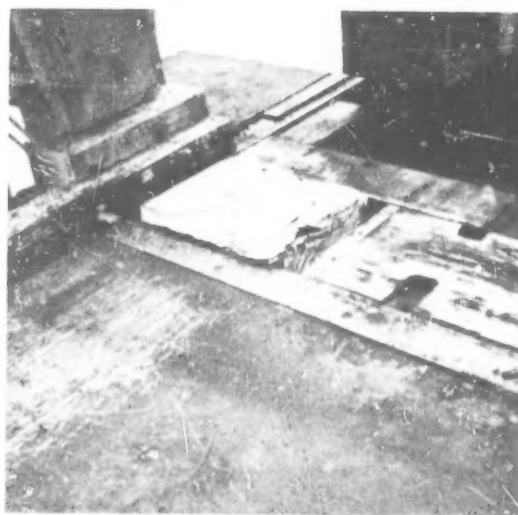
(5)



(6)



(7)

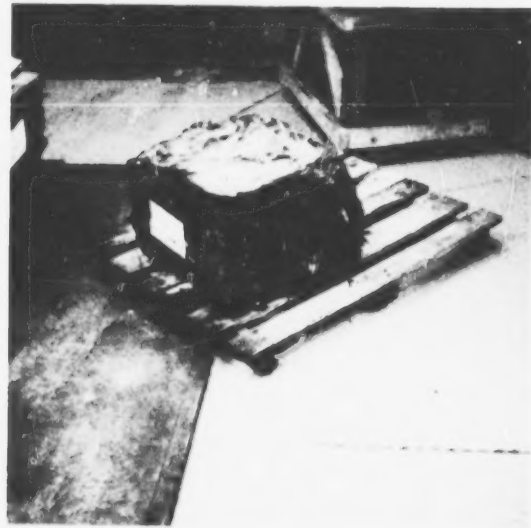


(8)

Compaction of Loose and Paper-Sacked Residential Wastes:
 (5), (6) Wastes in Charging Box
 (7) Compacted Bales of Loose Wastes Containing Shredded Tires
 (8) Ejection of Paper Sacked Bale after Compaction



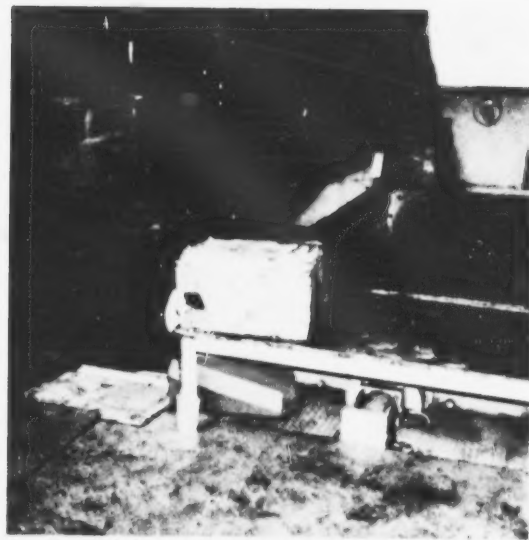
(9)



(10)



(11)



(12)

Individual Bales Compacted at about 3,500 psi:

a) Spring Cleaning Refuse of High Dirt Content: (9) Loose; (10) Paper-Sacked

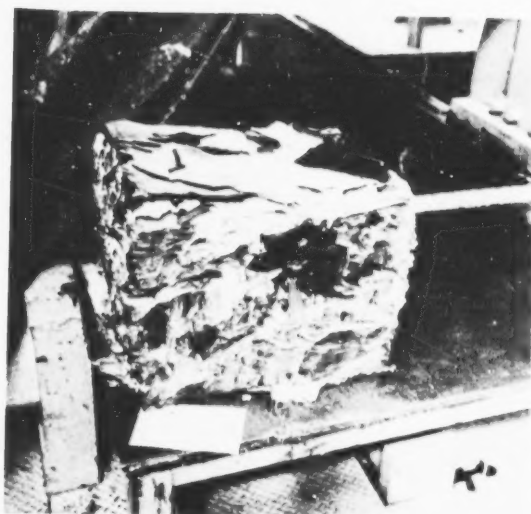
b) Winter Refuse of High Paper Content: (11) Loose; (12) Paper-Sacked



(5)



(6)



(7)

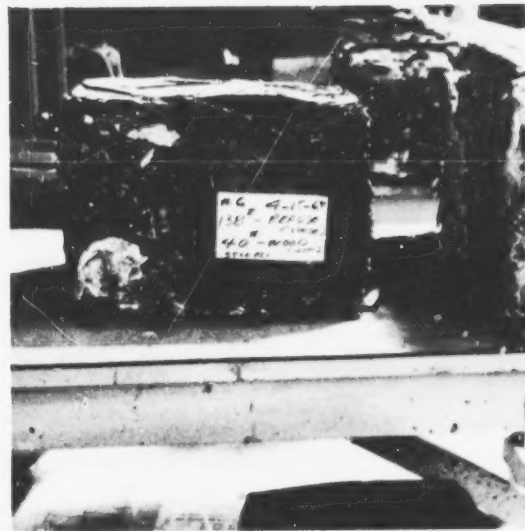


(8)

Compaction of Loose and Paper-Sacked Residential Wastes:
 (5). (6) Wastes in Charging Box
 (7) Compacted Bales of Loose Wastes Containing Shredded Tires
 (8) Ejection of Paper-Sacked Bale after Compaction



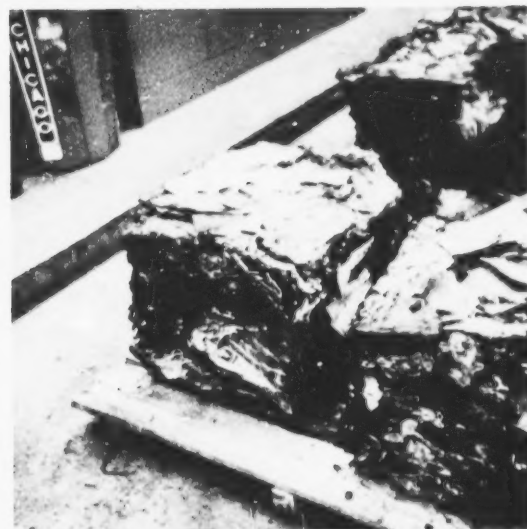
(13)



(14)



(15)



(16)

Compacted Winter Refuse — Loose and Paper-Sacked

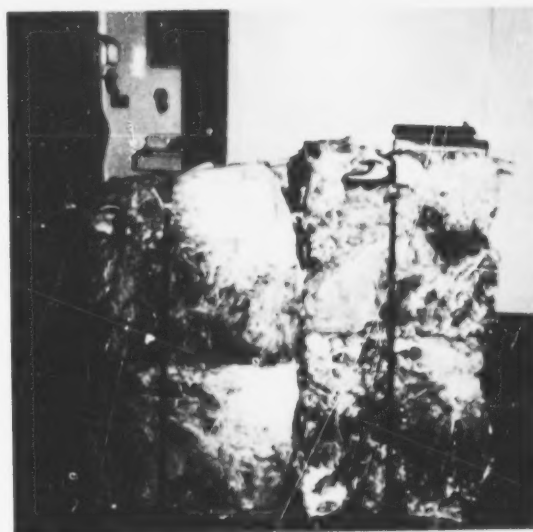
(13) Left Set 2,000 psi, Right Set 3,500 psi, Strapped to Pallets for Truck Transport

(14) Spring Refuse Containing Wood Chips

(15) and (16) High Dirt Content Spring Cleaning Refuse



(17)



(18)



(19)



(20)

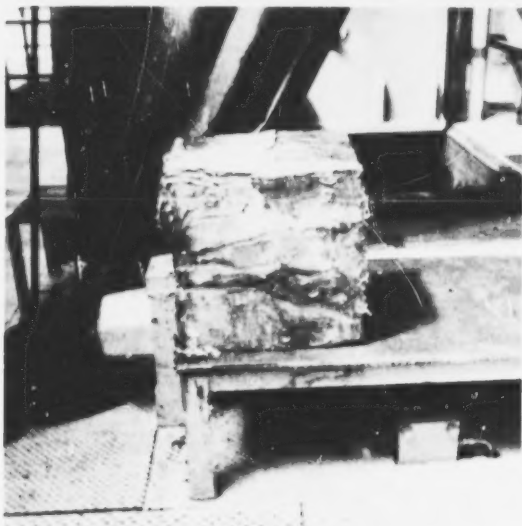
Bales Compacted at about 2,000 psi:

(17) Paper-Sacked Spring Refuse

(18) Paper-Sacked (left) and Loose (right) Winter Refuse, Strapped to Pallet for Truck Transport

(19) Spring Cleaning Refuse Loose

(20) Spring Cleaning Refuse Paper-Sacked



(21)



(22)



(23)



(24)

(21) and (22) Paper-Sacked Refuse, Large Bales, Compacted at about 3,500 psi
 (23) Temperature Measurement of Plastic Covered Bales Used for Gas Analysis
 (24) Appearance of Refuse Bale after 5 Days of Decomposition Inside Plastic Cover



(25)



(26)



(27)



(28)

- (25) High Dirt Content Refuse Compacted at about 2,000 psi for 5 Minutes
 (26) Spring Cleaning Refuse Compacted at about 1,000 psi for 10 Minutes (front) and High Paper Content
 Synthetic Refuse Compacted at 1,000 psi (back)
 (27) Synthetic Refuse Compacted at about 750 (left) and 1,000 psi (right) for 5 Minutes
 (28) Shredded Refuse Compacted at about 2,000 psi



(29)



(30)

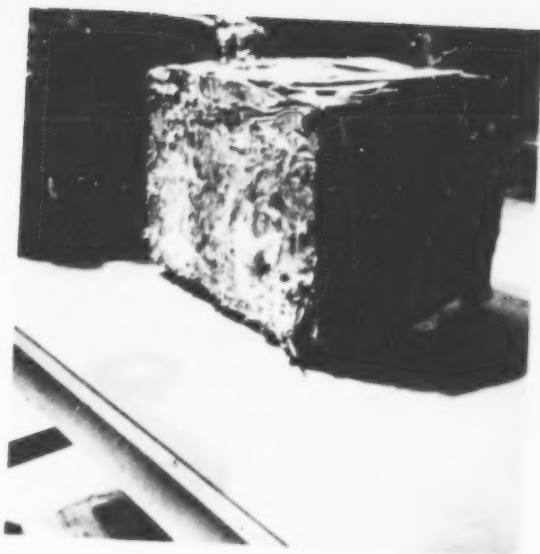


(31)



(32)

- (29) Paper-Sacked Refuse Compacted at about 750 psi for 5 Minutes
- (30) 1,000 psi for 5 Minutes
- (31) 1,000 and 1,500 psi for 5 Minutes
- (32) 2,000 psi for 5 Minutes



(33)



(34)



(35)



(36)

(33) Oversized Waste Bale

(34) Paper Mixture Bales Containing 45% (left) and 35% (right) of Water

(35) Large Bale Containing Dry Leaves, Clippings and Dirt

(36) Compacted Bale of Bedsprings (top). Refuse Mixtures with Ultra-High Metal and Can Content (bottom)



(37)



(38)



(39)



(40)

Compacted Bales after Handling and Relatively Long Term Exposure to Weather Conditions:
 (37) Paper-Sacked Residential Wastes
 (38) Spring Cleaning Residential Wastes Loose
 (39) Shredded Wastes
 (40) Paper Mixture Bales of High Initial Water Content

CHAPTER IV

THE STABILITY OF SOLID WASTE BALES IN TERMS OF RAIL-HAUL SYSTEMS

This chapter of the report deals with one of the key aspects of the total project: the stability of the compacted solid waste bales. As indicated in Chapter II the requirements for any given bale form and size mandate that the bale bear a relatively stable configuration until it is disposed of in a sanitary landfill.

SECTION ONE—BASIC STABILITY FACTORS AND CONCEPTS

In general, stability is defined as the tendency to remain in a given state or condition without spontaneous change. This implies the capability of possessing or developing forces equal to or greater than any disturbing forces capable of causing instability.

The term and concept of stability is applied in many ways in different fields. Even with respect to solid waste bales, stability might be considered primarily or exclusively in terms of, for example, chemical stability, thermal stability, and mechanical stability including specifically the aspects of dimensional stability and structural stability.

Within the context of this section of the report, the term stability is used to denote the mechanical stability of compacted solid waste bales. In particular, the term is used to denote the resistance of the compacted bales against their structural disintegration by the application of mechanical forces.

It is, of course, recognized that chemical instability induced by biological activity may ultimately be the major cause for any mechanical and/or structural instability of the bale. However, to become effective in this respect both the biological or chemical degradation forces appear to require a longer period of time than the "shelf life" needed for solid waste bales in rail-haul operations.

Concerning the bale itself, the mechanical stability has to be viewed with respect to the characteristics of a highly heterogeneous composite solid. As indicated throughout this report a solid waste bale, as a rule, represents neither a single solid nor a solid of uniform or even relatively uniform material composition and/or material distribution. Since the individual components of most solid waste bales exhibit both elastic and inelastic properties, the over-all characteristics of the bales might be considered akin to those of semi-elastic solids.

This finding is highly significant within the context of the current investigation. The structural

stability of solid waste bales is determined primarily by the strength of the adhesive or the interlocking bonds formed between the solid waste components by the application of pressure during compaction. Consequently these bonds may be loosened by either (a) the internal elastic forces or resiliency inherent in the material composition or (b) the application of external forces from the outside or (c) a combination of both force activities.

The expansion or springback forces developed within the bale are treated separately in Chapter III of this report. The major part of their activity occurs immediately and within a relatively short period of time after release of the compaction pressure. These forces and the counteracting cohesive forces determine primarily at that time, the volume, shape, and the inner structural stability of the bale.

As a result, bales which remain intact after exit from the press may, for practical purposes, be considered as being in equilibrium with respect to the interaction of their internal cohesive and expansive forces. But stability in terms of just the bale, i.e., cohesiveness of the unit and retention of configuration, is not enough for rail-haul. Concerning both rail transport and the material handling involved, the stability of bales must also be established with regard to forces applied from the outside through impact, vibration, pressure, and load.

SECTION TWO—STABILITY TEST CONSIDERATIONS

To ascertain the stability of compacted bales with respect to solid-waste rail-haul, it is necessary to consider the operating requirements of both the individual system elements and the total system itself. In particular, it is necessary to ascertain: bale stability in terms of rail transport, bale handling at the transfer station as well as the disposal site, and bale storage conditions and time.

I. BALE STABILITY IN TERMS OF RAIL TRANSPORT

Within the solid-waste rail-haul environment the shipped goods are subject primarily to longitudinal and/or lateral and/or vertical shock and vibration forces. The total amount of these force applications is, of course, influenced by factors such as travel distance and travel time.

1. Longitudinal Shock and Vibration

Longitudinal vibration does not exist at amplitudes sufficient to cause damage to the lading.

This vibration is caused when the springs of one wheel truck move vertically 180 degrees out of phase with respect to the spring of the other truck. This vibration often is referred to as pitching or rotational vibration.

All longitudinal shocks involve an impact between two rail cars and generally the cars are either traveling in the same direction or one is standing. In moving trains a certain amount of movement must be allowed between the car-end connections. This, in turn, allows for some slack in car movements within a train. During travel this slack is stretched or taken up because of variations in track gradient, curves, braking, or acceleration. Due to the total car weights and traveling speeds involved, these slack movements result in longitudinal shocks in either, or both, directions. However, even a severe run-in during such movements is generally equivalent to only a 5-mile-per-hour impact.

Experience has shown that most commodities are not damaged by impacts at speeds of 5 or less miles per hour. But damage does occur during shipment and the railroad yard operations have been found to be the source of most impact damages. This holds true regardless of whether the cars are flat switched or sorted by modern gravity systems.

The typical performance of a railroad classification yard with respect to the generation of impacts of varying severity is given in Table 38. The data were established by the Technical Research Department of the Penn Central Railroad and by Pullman Standard, a Division of Pullman Incorporated. The Pullman Standard figures are based on 1,568 car impacts, measured over a period of 3

months in 1950. The Penn Central figures are based on systemwide averages of 10,000 measurements per year over a 2 year period.

The data in Table 38 indicate that, contrary to popular belief, only about 15 percent of all yard impacts exceed impact speeds of 6 miles per hour. The average impact appears to occur at a speed of 5 miles per hour or less. In terms of railroad operations, impact speeds of 6 or more miles per hour are considered "rough handling" while impact speeds between 5 and 6 miles per hour are considered borderline cases. In most cases, the forces of a longitudinal shock exist for about 0.1 second.

However, a loaded rail car might be handled several times in a manner akin to classification yard operations. In a rail-haul system this might occur during switching at the transfer station or at the disposal site and during the assembling of a train enroute, e.g., the adding of cars from communities included in the makeup of a single train.

The probability of impact occurrence in sequential switching operations has also been established by the Penn Central Technical Research Center. Data on 20,000 measurements are given in Table 39 on the following page.

The data indicate, for example, that the probability of a car being struck by an impact of over 6 miles per hour while passing through three switching yards is about 1 in 3. In five switching yards, an impact at a speed of more than 6 but less than 7 miles per hour might happen to every other car.

From these data it can be concluded that, with

TABLE 38
Typical Distribution of Impacts Occurring in a Railroad
Classification Yard

Impact Speed	Percent of Total Number of Impacts	
	Pullman Standard Data	Penn Central Data
below 5 mph	36	} 70
at 5 mph	34	
at 6 mph	17	17.4
at 7 mph	7	6.0
at 8 mph	3	3.1
at 9 mph	2	2.3
at 10 mph & over	1	1.2
	100%	100.0%

Source: Technical Research Center, Penn Central Railroad Company, "The Railroad Environment, A Guide for Shippers and Railroad Personnel," Cleveland, 1966

respect to stability, a solid waste bale should be capable of withstanding at least one impact of 6 to 7 miles per hour during rail transport. In addition, the bale should be capable of sustaining the "normal" impacts occurring during shipment.

2. Lateral Shock and Vibration

Lateral vibrations frequently are caused by out-of-phase vertical vibrations resulting from a vertical out-of-phase movement of the springs and wheels. They also may be excited by turnouts, switches, rails out of alignment and/or worn truck parts. Lateral vibrations are seldom due to curves.

Lateral vibration forces cause damage only in special cases. Furthermore, lateral vibrations, strong enough to cause an unrestrained package to merely move from its position, occur for only 1 percent of the total travel time under normal operating conditions. However, packages with a center of gravity higher than the width of their bases may be damaged by the packages tipping over.

Lateral shocks generally result from forces exerted in the vertical and longitudinal planes. In almost all cases they have a time duration of less than .02 seconds and are seldom severe. Due to the short duration of these shocks, the normal protection which is applied to the lading regardless of rail transport considerations has proven to be sufficient, as a rule, to guard shipments against lateral vibrations.

On the basis of the foregoing findings it can be concluded that a relatively tight load is all that is necessary to protect a load including bales against lateral shock and vibration. Much will depend, of course, on the smoothness or frictional surface characteristics of the units in a given load. If the surfaces of the packages or units are not slippery but

somewhat rough, then it is usually not required that filler material be provided for those spaces of the car width not occupied by the lading.

3. Vertical Shock and Vibration

Vertical vibrations are very seldom the cause of damage to the lading if it is properly loaded. Continuous vibration, at a force of about 0.25 percent of the weight of a package, will average about 3 to 8 cycles per second. Heavy loads, as a rule, reduce the vibration rate to about 3 cycles per second. Because of the resiliency of the springs generally used, lightly loaded cars experience higher vertical accelerations than cars loaded to their full carrying capacity.

The shock forces resulting from over-the-road operations are rarely severe in the vertical plane. But in yard operations these shocks may increase to about double the normal force. Fortunately, vertical shocks are of short duration lasting approximately .01 seconds.

However, vertical shocks gain significance in terms of the height to which individual units are stacked in or on a rail car. The lowest part of the lowest package must be capable of carrying not only the total weight placed on top of it but also the dynamic load generated by this weight through the vertical accelerations.

These findings show the importance of determining the bale stability specifically with respect to the height of loading during transport. Since the maximum loading height of a rail car approximates 8 to 9 feet, and since the density of solid waste bales including oversized items averages from 50 to about 80 pounds per cubic foot, it is desirable that the lowest portion of a bale be capable of supporting

TABLE 39
Probability of Impact Occurrence in Sequential
Switching Yards

No. of Yards	Impact Speed					
	to 5 mph	over 5 mph	over 6 mph	over 7 mph	over 8 mph	over 9 mph
1	.700	.300	.126	.066	.035	.012
2	.490	.510	.235	.128	.069	.024
3	.345	.655	.332	.185	.102	.036
4	.240	.760	.416	.240	.133	.047
5	.168	.832	.490	.290	.163	.059

Source: Technical Research Center, Penn Central Railroad Company, "The Railroad Environment, A Guide for Shippers and Railroad Personnel," Cleveland, 1966

about 720 pounds per square foot under transport conditions.

If oversized wastes are excluded from the compaction process, the compacted bales average 50 to 60 pounds per cubic foot after springback. In these cases the lowest portion of the bale would, therefore, have to carry only a maximum of about 540 pounds per square foot under rail transport conditions.

Finally, the above findings suggest also that bales in less than fully loaded cars are subject to more severe transport conditions than those transported in fully loaded cars. This fact must be remembered in evaluating the shipment tests made during this project, because none of the rail test cars was loaded down to approach its load carrying capacity. Actual rail-haul systems will, of course, operate with fully loaded cars as much as possible.

4. Travel Distance and Time

The frequency of the application of the destructive forces described above is closely interrelated with the travel distance, other conditions being equal. In addition, the effects of the force application may also be influenced by the time intervals occurring between the successive force incidents. A sufficiently long time interval may, for example, allow any recovery forces present to become effective.

In current rail-haul analyses it is planned to ship compacted solid wastes by rail over distances of about 50 to 150 miles. At an average train speed of 25 miles per hour the bales would thus be 6 hours in actual transport. This would be reduced to 3 hours if the train speed were doubled. Freight trains travel today, as a rule, at speeds between 25 and 50 miles per hour. Consequently, for current solid-waste-rail-haul systems, the bales should be capable of surviving a rail transport of at least 150 miles distance and of 3 to 6 hours duration.

II. BALE STABILITY IN TERMS OF MATERIAL HANDLING

Bale handling in solid-waste rail-haul will occur almost exclusively at the transfer station and at the disposal site. In each case, the operations concerned require the following functions:

- a. to pick up one, or more than one, bale;
- b. to move the bale or bales; and
- c. to deposit or drop the bale or bales at the place of destination.

For such equipment as cranes, fork-lift trucks, conveyors, slides, or manually operated tools, the forces applied are primarily those of pressure, impact and/or vibration. In principle, these forces are identical to those encountered during rail transport.

The material handling equipment commonly used is capable of meeting any requirements for the safe handling of the items involved. Thus, material handling equipment can be purchased readily to fit the condition of the bale. However, this is not true with respect to other phases of the operation. The bale must and can be made to fit the transport conditions encountered with commonly available railroad freight cars, if specialized cars and transport regulations are to be avoided.

It is reasonable to assume that a bale capable of rail transport can also be handled successfully at both the transfer station and the disposal site. This is based on the fact that all goods damaged during rail transport had been handled successfully before they were placed on a railroad car. Similarly, a rail-haul system for solid waste bales is apparently much more demanding in the transport phase than in the few material handling operations involved.

III. BALE STABILITY IN TERMS OF BALE STORAGE AND SHELF LIFE

A rail-haul system for the shipment of baled solid wastes may involve many operational variations. These variations concern primarily the frequency of bale pickup at the transfer stations. For example, it is conceivable that from small transfer stations, processing about 50 tons of solid waste per day, the bales may be picked up only once or twice per week. In contrast, large transfer stations will, in current planning, receive a daily pickup service.

As a result, the age of the solid waste bales shipped becomes significant. Assuming a maximum 24-hour transport time and a once-per-week pickup, it is necessary that 8-day-old bales be suitable for a 150-mile transport. In turn, 9-day-old bales would have to be suitable for the disposal site operations.

Any variations in the frequency of pickup require, of course, that the bales be stored—probably by stacking. However, this should not present difficulties since the load put on the lowest bale in storage is a static load rather than a dynamic load. Thus, the load sustained in storage is less than the load sustained by the lowest bale during rail transport if the storage is 8 to 9 feet high.

Rail-haul loading considerations and perhaps even the weight of the bales suggest that the height of bale storage be limited to 8 to 9 feet. This implies that storage shelves might have to be constructed, if a higher stacking of the bale loading units is necessary. This implies also that specific storage tests are not required with respect to bale stability, if the bales survive shipment tests which incorporate realistic loading height conditions.

IV. TEST SELECTION WITH RESPECT TO BALE STABILITY REQUIRED FOR SOLID-WASTE RAIL-HAUL SYSTEMS

The American Society for Testing and Materials has established many methods for testing the strength of materials and packages in terms of their mechanical stability. These tests include static and shock load capacity, drop, incline impact, and vibration tests. Some of these tests require special equipment such as a hexagonal revolving drum or vibration tables. Others merely specify a particular way by which a specimen is handled as, for example, the roll-over test.

The information presented thus far indicates that the impacts and vibrations generated during rail transport are the major destructive forces which the bale must sustain. Thus, within the scope of this project it is of prime concern to test the rail transport impact and vibration forces with respect to their effect on the structural stability of the bale.

In this context it might be mentioned that any minor bale deformation caused in storage or in handling and transport is of less concern than the structural stability, i.e., the cohesiveness of the bale. First, the appearance of solid waste bales with respect to their form is not critical. Second, the rail-haul system can be designed, within the limits given in Chapter II, to accommodate deformed as well as non-deformed bales. Third, variations in volume and shape of the bales must be anticipated within certain ranges, depending upon the kind and condition of the input materials. In terms of rail-haul, it is the cohesiveness of the bale which represents one of the key bale performance specifications.

The selection of the specific stability tests conducted during the present study was made primarily in consideration of the over-all time limitations, the professional talent available, and prudence in the expenditure of funds. On this basis it was decided to obtain the necessary information on bale stability by starting with selected exploratory experiments on bales of a very broad variety, and by designing each of the subsequent tests in the light of the findings obtained through previous tests. Following this approach, it was specifically decided to conduct series of different but interrelated tests including:

- a. one series of vibration and impact tests carried out under laboratory conditions and involving bales of widely varying characteristics,
- b. two rail transport tests covering different test conditions with respect to the bale type and characteristics as well as the bale loading

configurations,

- c. two sets of drop tests involving different kinds of bales subjected to transport as well as bales of varying ages after compaction, and
- d. a continuous observation of bale behavior during the numerous bale handling operations required at the test site.

Considering the nature, number, and variety of the tests performed, and considering the scope of this project, it can be concluded that the mechanical stability of the compacted bales was ascertained on a rather comprehensive scale. The composite information obtained by these tests may be judged to be at least adequate for the development of executive decisions on the stability of the bales for rail-haul operations.

SECTION THREE—VIBRATION AND IMPACT TESTS MADE UNDER LABORATORY-SCALE CONDITIONS INVOLVING TWELVE BALES WITH WIDELY VARYING CHARACTERISTICS

The laboratory stability tests were conducted at the Idea Center of Acme Products, a Division of Interlake Steel Corporation. The Idea Center—a certified National Safe Transit Committee laboratory—emphasizes strapping research. It is equipped with almost every type of strapping tool and test equipment needed to ascertain the stability of whatever item under a great variety of shipment and material handling conditions. The professional capabilities and the facilities of the Acme Center were made available to the project without cost.

The objective of the tests described below was to obtain, in an exploratory manner, indications of the handling and transport stability of bales exhibiting a selected set of widely varying characteristics.

I. THE TEST SETUP

In line with the above objective, the tests were set up to yield criteria sufficient to guide both the on-going bale development experiments as well as the subsequent stability tests. Specifically, the tests were designed to measure in broad increments the resistance to destruction of various types of bales compacted at different pressures and containing loose, sacked, and shredded wastes. In addition, the tests were designed to ascertain whether strapping of the bales is necessary for rail-haul.

1. The Test Equipment and Basic Test Procedure

To test for the stability of the bales, it was decided to subject each bale first to vibration impacts and then to direct impacts of increasing force application. As has been pointed out previously, vibration impacts are by nature less severe than the

direct impacts encountered in a rail-haul system. The vibration tests were made on a Gaynes Vibrator and the impact tests on an incline impact tester.

The Gaynes Vibrator simulates a railroad trip by subjecting the test specimen to a concentrated number of vibration impacts, the strength of which is related to the weight of the specimen. The simulation is accomplished by vibrating the unit in such a manner that the test specimen floats suspended at a very small distance above the surface of the vibrator.

The test procedure requires that a sheet of paper be placed under the test specimen and the vibration cycles per minute be increased until the paper can be moved freely beneath the load. In this condition, the test specimen experiences a force of one "g" or an acceleration of about 32 feet per second.

To gain time, it was decided to vibrate two bales simultaneously. However, since the bales were not of equal weight, it was necessary to adjust the vibration cycles to the vibration force requirements of the heavier bale. As a result, the lighter bale always received vibration impacts of a greater force than indicated by the test results.

The Gaynes Vibrator was capable of simulating a railroad trip of 1,000 miles in half an hour. However, to utilize the available efforts best, it was decided to simulate a rail trip of about 300 miles, which is twice the maximum shipping distance currently considered for solid-waste rail-haul.

The incline impact tester is also a very versatile instrument. To obtain realistic impact ranges, the incline was set at 10 degrees to the horizontal and the accelerations were gauged to conform to rail transport impact zone standards. To generate impacts of increasing severity, the impact test sequence was set as follows:

In evaluating the above impact sequence, it must be recognized that impacts in Zone 3 constitute "rough handling." Impacts in Zone 4 are frequently classified in railroad operations as "severe rough handling" while impacts in Zone 5 approach the magnitude of collision impact forces.

To ascertain the impact stability of the bales under all—within reason—severe solid-waste-rail-haul operating conditions, it was decided to subject each bale to the impact test series twice. Thus, each bale received 12 consecutive impacts in the sequence described in Table 40. The first six impacts were applied in a direction parallel to the last compaction stroke and the second six impacts were applied in a direction perpendicular to the last stroke. In this context it should be remembered that the highest compression pressures were always applied during the last compaction stroke.

2. The Bale Sample

The sample of bales used in this test series was selected to provide the maximum amount of broad guideline data possible under the existing operating constraints. Accordingly, it was decided to include two sets of bales compacted at gauge pressures of about 2,000 and 3,500 psi. The bales were all made from off-the-truck household refuse which was compacted either as it was in the loose state, contained in refuse collection paper sacks, or shredded. Furthermore, one set of the bales of each category was strapped and a corresponding set was not strapped.

The shredded household refuse came from Madison, Wis., where it was shredded in a Heil-Gondard refuse size-reduction machine. The other household wastes came from one single

TABLE 40
Conbur Test

Impact Sequence and Number	Test Performance Specifications			Equivalent Rail Transport Impact Zone Number
	Incline	Length of Incline	Impact Speed	
	(degree)	(inches)	(mph)	
1	10	24	4 - 5	2
2	10	30	6 - 7	Low 3
3	10	36	6 - 7	3
4	10	42	8 - 9	Low 4
5	10	48	8 - 9	4
6	10	58	8 - 9	5

truckload of Chicago refuse. The Chicago refuse contained a significant amount of spring yard-cleaning materials as described in Chapter III of this report. All bales were produced the day before the vibration and impact tests.

Concerning the strapped test bales, all strapping was applied within 1 and 5 minutes after bale exit from the press. Two straps were put on each bale in a direction parallel to the direction of the last compression stroke. After some exploratory experimentation, it was decided to place the straps 4 inches from either end of the bale, leaving a distance between the straps of about 15 inches.

The same type of commercially available straps was used for each bale. This strapping is cataloged as Interlake 5/8 x .020 inch Regular Duty Strapping and has a tensile breaking strength of 1,440 pounds. The strapping was applied with an Interlake Tensioner Model No. B5F6, Sealer Model No. C1A5, and Seal No. 51.

The total sample used for the laboratory vibration and impact tests consisted of 12 bales. A summary of the bale characteristics is given in Table 41. The summary indicates that variations in both the bale properties and bale production were duly recognized in the makeup of the sample. For example, one bale had a density of 50.76 pounds per cubic foot and an over-all volume of 3.62 cubic feet, while another bale of the same type and category had a density of 70.68 pounds per cubic foot and an over-all volume of 3.51 cubic feet.

II. THE TEST RESULTS

The results of the vibration and impact tests performed at the Acme Idea Center are summarized in Table 42. In the over-all, the data indicate that all bales were exceedingly stable regardless of whether they were strapped or not, or whether they were compacted at lower or higher pressures.

The table also gives the over-all bale evaluation ratings used. These evaluations were made by observation and judgment and applied to all the bales; not only during this stability test, but also during the compaction experiments. The grades or ratings ranged from "poor" to "very good." In making these judgments, factors such as the following were taken into account: compactness, sharpness of the edges, loose portions, cracks, and appearance. It should be highlighted that these evaluations rated the bales relative to each other in terms of the total number of bales made during the project.

A specific analysis of the foregoing data shows that even the four bales, which were made from loose household refuse of high dirt content and which, moreover, were judged to be comparatively poor even

before the testing, survived both the vibration and impact tests. These four bales, considered the worst bales of the lot, were subsequently subjected to an additional vibration test set up to apply vibrations with a minimum force of one "g" until one of the bales disintegrated.

This objective was achieved when Bale No. 1 (Test 5), the poorest bale of the sample, broke into two sections, both of which had great spillage. The application of the additional vibrations necessary for the destruction of the first bale required 10 minutes at 195 cycles per minute. Thus, in terms of rail transport, the additional vibrations represent a shipping distance of about 330 miles.

As a result, the weakest bale of the total sample was still capable of withstanding, before being destroyed as a bale, a rail trip exceeding 600 miles. This is four times the distance currently contemplated for the rail-haul of solid waste. In addition, the weakest bale was also capable of surviving at least 12 impacts including two impacts approximating collision force.

The other three bales made from loose refuse remained quite stable in spite of this additional 330-mile trip. Bale No. 7, although not strapped and only compacted at 2,000 psi, held well. The other two bales, both strapped, survived the simulated additional shipping distance in an even better condition.

III. CONCLUSIONS

The test results support without any doubt the conclusion that all the bales, without exception, were extremely stable in terms of the total system requirements for the rail-haul of solid wastes. Actually all the bales exceeded, to a considerable degree, the stability specifications as developed in detail at the beginning of this report section.

It was apparent that strapping improves the stability of the bales.

However, since the unstrapped bales withstood the vibration and impact tests successfully, it was decided not to conduct additional strapping tests within the present project. It is understood that the Acme Products Division of Interlake Steel Corporation, is pursuing this matter further.

Finally, the vibration and impacts of the magnitude applied in these tests appear not to lower the evaluation grades as applied to the bales throughout the stability test increments. A bale judged "good" before testing tended, as a rule, to remain in this category after testing; and a bale judged "poor" still survived all the tests in this category.

In the over-all, the results of the laboratory tests

TABLE 41
Selected Information on the Twelve Bales Used for the Vibration
and Impact Tests Under Laboratory-Scale Conditions

Test Number	Bale Number	Type of Solid Waste Used	Compaction Pressure (gauge psi)	Total Weight of Bale after Compaction (pounds)	Density One Minute after Exit from Press (lbs/cuft)	Density One Day after Exit from Press (lbs/cuft)	Density Decrease Within One Day (%)	Fortification of Bale by Strapping
1	11	Madison, Wis. Household Ref. SHREDDED	2000	239.5	75.8	63.99	16	Not Strapped
2	10		2000	256.0	74.4	66.15	11	Strapped
1	9	Same	3500	221.5	70.8	58.41	18	Not Strapped
2	8		3500	238.5	71.0	64.91	9	Strapped
3	13	Chicago, Ill. Household Ref. PAPERSACKED	2000	167.5	67.0	51.06	24	Not Strapped
4	12		2000	170.0	69.0	54.70	18	Strapped
3	5	Same	3500	194.5	65.5	54.89	16	Not Strapped
4	15		3500	198.5	73.5	65.02	12	Strapped
5	7	Chicago, Ill. Household Ref. LOOSE	2000	183.5	59.8	50.76	15	Not Strapped
6	6		2000	248.0	72.7	70.68	3	Strapped
5	1	Same	3500	182.0	70.3	65.66	7	Not Strapped
6	18		3500	145.0	60.4	54.84	9	Strapped

Table 42. Summary of Results from the Vibration and Impact Test Series Conducted Under Laboratory-scale Conditions

TEST CHARACTERISTICS AND OBSERVATIONS	Test Number 1		Test Number 2		Test Number 3	
	Bale No. 11	Bale No. 9	Bale No. 10	Bale No. 8	Bale No. 13	Bale No. 5
Bale Characteristics						
Material	Shredded Madison, Wis. Household Ref.	Shredded Madison, Wis. Household Ref.	Shredded Madison, Wis. Household Ref.	Shredded Madison, Wis. Household Ref.	Paper-cracked Chicago, Ill. Household Ref.	Paper-cracked Chicago, Ill. Household Ref.
Compaction Pressure	2000 psi	3500 psi	2000 psi	3500 psi	2000 psi	3500 psi
Total Weight	239.5 lbs	221.5 lbs	256.0 lbs	238.5 lbs	167.5 lbs	194.5 lbs
Fortification	No strapping	No strapping	Strapped	Strapped	No strapping	No strapping
Vibration Characteristics						
Time	9 minutes	9 minutes	9 minutes	9 minutes	9 minutes	9 minutes
Cycles per Minute	215	215	175	175	175	175
Equivalent Railroad Miles	300	300	300	300	300	300
Force Applied	One "g"	More than one "g"	one "g"	more than one "g"	more than one "g"	one "g"
Condition of Bale BEFORE Vibration						
Overall Bale Evaluation	Very good	Very good	Very good	Very good	Very good	Good
Specific Defects	Many small cracks parallel to 2nd ram	Several cracks parallel to 2nd ram	A few small cracks	One major crack, parallel to straps	Bundle did bulge and was not cubical	Some skewing on top surface, unlevel
Condition of Bale AFTER Vibration						
Stability	Stable	Stable	Stable	Stable	Stable	Stable
Specific Defects	Some flakes dropped off, cracks didn't increase noticeably	Crack increase no apparent; light spillage	Some flaking on one side, slight spillage	Large crack did not increase, slight spillage	Some overall growth	Some skewed paper on top surface
Overall Bale Evaluation	Very good	Very good	Very good	Very good	Very good	Good
Condition of Bale AFTER 12 Consecutive Impacts						
Applied in Two Identical Series of Six Impacts Each Increasing in Acceleration from 4 to 11 Miles per Hour and in Distance from 28 to 58 inches						
Stability	Stable	Stable	Stable	Stable	Stable	Stable
Specific Defects	Cracks become fissures parallel to 2nd ram; appears as if fissures affect only one side, not deep	Cracks appeared to open noticeably but bale held well	Droppings from one corner and side, still strapped tightly	Some droppings, crack did not increase possibly because the strapping might have held pieces together	Very little spillage, some growth	Little spillage but more growth on skewed top surface
Overall Bale Evaluation	Good	Good	Good	Good	Very good	Good

Table 42. (continued) Summary of Results from the Vibration and Impact Test Series Conducted Under Laboratory-scale Conditions

TEST CHARACTERISTICS AND OBSERVATIONS	Test Number 4		Test Number 5		Test Number 6	
	Bale No. 12	Bale No. 15	Bale No. 7	Bale No. 1	Bale No. 6	Bale No. 18
Bale Characteristics						
Material	Papersacked Chicago, Ill. Household Ref.	Papersacked Chicago, Ill. Household Ref.	Loose Chicago, Ill. Household Ref.	Loose Chicago, Ill. Household Ref.	Loose Chicago, Ill. Household Ref.	Loose Chicago, Ill. Household Ref.
Compaction Pressure	2000 psi	3500 psi	2000 psi	3500 psi	2000 psi	3500 psi
Total Weight	170.0 lbs	198.5 lbs	183.5 lbs	182.0 lbs	248.0 lbs	145.0 lbs
Fortification	Strapped	Strapped	No strapping	No strapping	Strapped	Strapped
Vibration Characteristics						
Time	9 minutes	9 minutes	9 minutes	9 minutes	9 minutes	9 minutes
Cycles per Minute	190	190	190	190	190	190
Equivalent Railroad Miles	300	300	300	300	300	300
Force Applied	more than one "g"	one "g"	one "g"	one "g"	one "g"	more than one "g"
Condition of Bale BEFORE Vibration						
Overall Bale Evaluation	Very good	Good	Fair	Poor	Fair	Very good
Specific Defects	Unitized well with strapping, loose paper sack on top surface	Tight bale, but one strap applied not quite perpendicular to side, appeared to spread bundle apart	Appeared loosely compacted, contained a lot of dirt	Unstable appearance contained considerable dirt	Some rebound around straps	None
Condition of Bale AFTER Vibration						
Stability	Stable	Stable	Fairly stable	Fairly stable	Fairly stable	Stable
Specific Defects	Some growth perpendicular to straps	Some growth and spread in middle	Some fluffing, growth, and spillage	Quite a bit of spillage and loosening up	Some fluffing, spillage, and rebound	Very little spillage
Overall Bale Evaluation	Very good	Good	Fair	Poor	Fair	Very good
Condition of Bale AFTER 12 Consecutive Impacts						
Applied in Two Identical Series of Six Impacts Each Increasing in Acceleration from 4 to 11 Miles per Hour and in Distance from 28 to 58 inches						
Stability	Stable	Stable	Fairly stable	Fairly stable tho loose bale	Fairly stable	Stable
Specific Defects	No change	Small increase of spread at middle	Bale appears quite ragged, some spillage	Bale began to open up, spillage	Some spillage; strapping appears to help in unitizing	Some spillage
Overall Bale Evaluation	Very good	Good	Fair	Poor	Fair	Very good

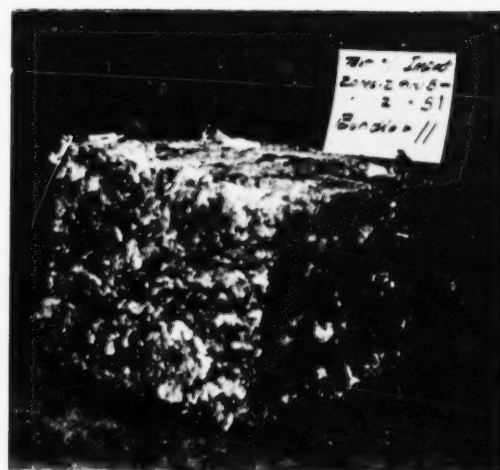
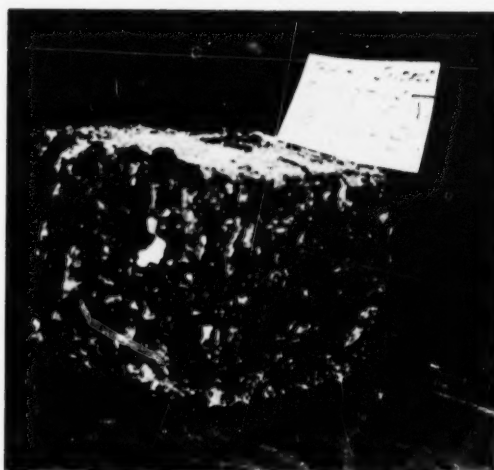
TEST NO. 1
CONSISTENCY - SHREDDED
STRAPPING - NONE



Before Vibration

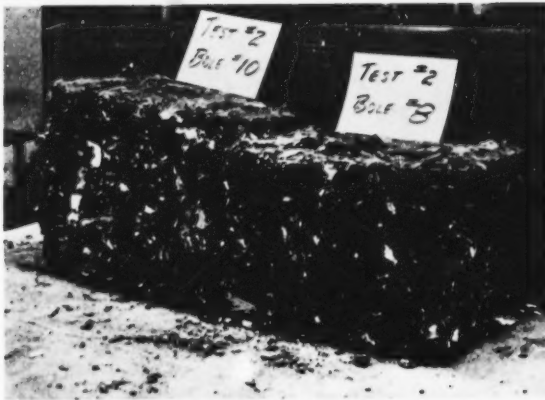


After Vibration



After Impact

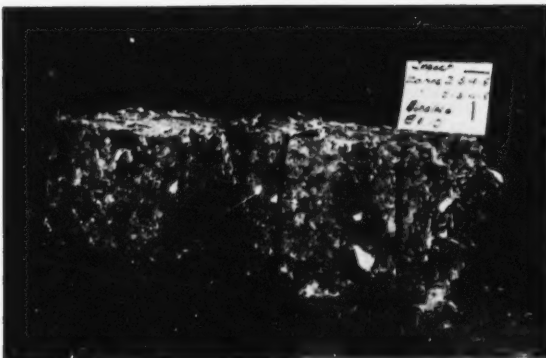
TEST NO. 2
CONSISTENCY - SHREDDED
STRAPPING - 5/8 x .020 inches



Before Vibration



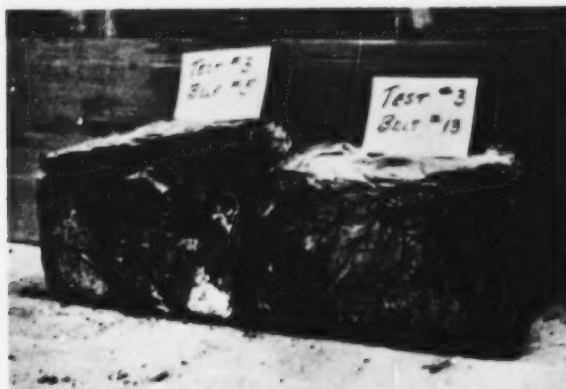
After Vibration



After Impact

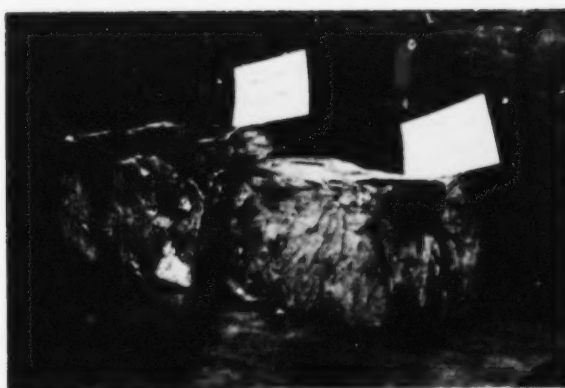
TEST NO. 3
CONSISTENCY - HOUSEHOLD IN PAPER SACKS
STRAPPING - NONE

Before Vibration



After Vibration

After Impact



TEST NO. 4
CONSISTENCY - HOUSEHOLD IN PAPER SACKS
STRAPPING - 5/8 x .020 inches



Before Vibration



After Vibration



After Impact

TEST NO. 5
CONSISTENCY - HOUSEHOLD LOOSE
STRAPPING - NONE

Before Vibration



After Vibration

After Impact



TEST NO. 6
CONSISTENCY - HOUSEHOLD LOOSE
STRAPPING - 5/8 x .020 inches



Before Vibration



After Vibration



After Impact

TEST NO. 7
CONSISTENCY - HOUSEHOLD LOOSE
STRAPPING - 2 STRAPPED (5/8 x .020 inches)
2 UNSTRAPPED



The bales pictured above were vibrated and impacted previously, i. e.,
Test No. 5 - Bundles No. 7 and No. 1
Test No. 6 - Bundles No. 6 and No. 18
Test No. 7 is a photo before vibration to destruct

SECTION FOUR—FIRST 700 MILE RAIL TEST SHIPMENT INVOLVING 40 BALES WITH SELECTED CHARACTERISTICS

I. THE TEST SETUP

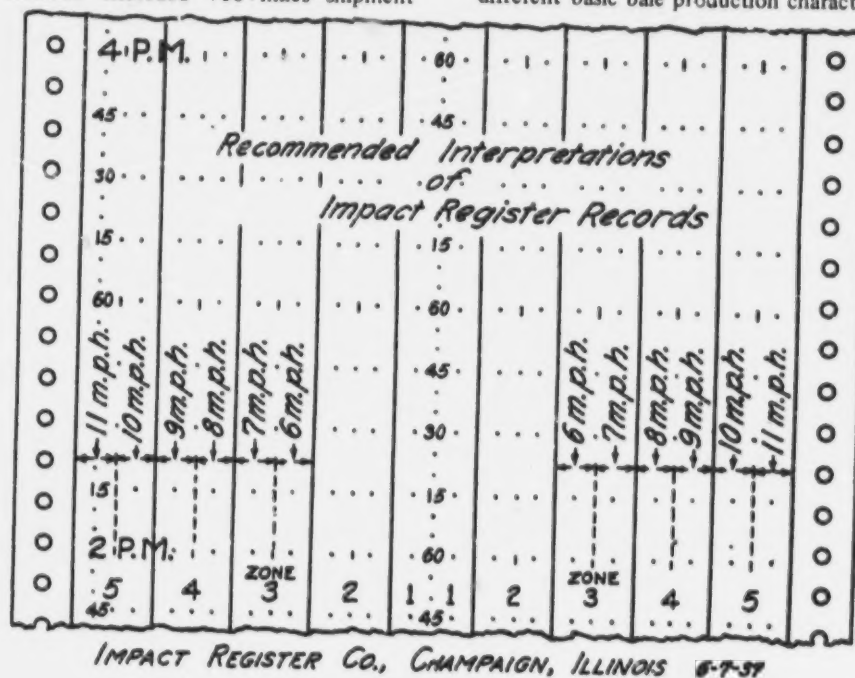
1. Rail Equipment, Transport Distance and Route

The car was moved by regular freight trains. The transport distance exceeded 700 miles—shipment

The car was equipped with an impact recorder which was mounted on the car floor. This instrument was attached to the car in Chicago and removed in Cleveland. By that time it had registered more than 12 feet of chart. An example of a basic impact recording chart indicating the impact interpretations is given in Figure 23.

2. The Bale Sample

The test sample was designed to highlight four different basic bale production characteristics. These



104

characteristics' pertain to the compaction pressures used and to the nature of the household refuse before compaction. Specifically, the test sample breaks down as follows:

percent of the time the bales were in the railroad environment. The transit time breaks down in three segments as follows: (a) Chicago, Illinois - Elkhart, Indiana-3.5 hours; (b) Elkhart - Toledo, Ohio-3.0

TABLE 43
Composition of Bale Sample for First Rail
Test Shipment

Nature of Household Refuse before Compression	Number of Bales	Compression Pressures (gauge psi)
Papersacked	10	2000
Papersacked	10	3500
Loose	10	2000
Loose	10	3500

The production of the 40 bales required almost one full working week and thus the bales were 1 to 4 days old at the time of the shipment. None of the individual bales or the bale sets were strapped during the rail transport from Chicago to Cleveland and back.

3. The Loading Configuration

The bales were placed on 3 x 4 foot pallets immediately after compaction to facilitate trucking from the test site to the rail car loading area. Twenty-four bales were put on six pallets in single layers, four bales per pallet. The remaining 16 bales were stacked on two pallets in two layers or eight bales per pallet. The bales, as illustrated in Figure 24 on the following page, were stowed in each corner of the rail car, two pallets per corner. The two pallets were stowed as close to each other as possible.

To simulate variations in the load, that a bottom bale might have to carry during transport, it was decided to burden some samples with a set of sandbags weighing 30 pounds each. Specifically, one single layer of eight bales in one corner was burdened by a weight of 1 ton of sand per square yard. Another single layer of eight bales in another corner was loaded with 2 tons of sand per square yard. Including the weight of the bale, this represents a static load on the bottom of the bale of 280 and 500 pounds respectively. All loads were, of course, secured by bulkheads and bracing.

II. THE TEST EXECUTION AND RESULTS

The test car was 2 1/2 to 3 days enroute from Chicago to Cleveland. However, the actual transit time amounted to only about 9 hours or about 15

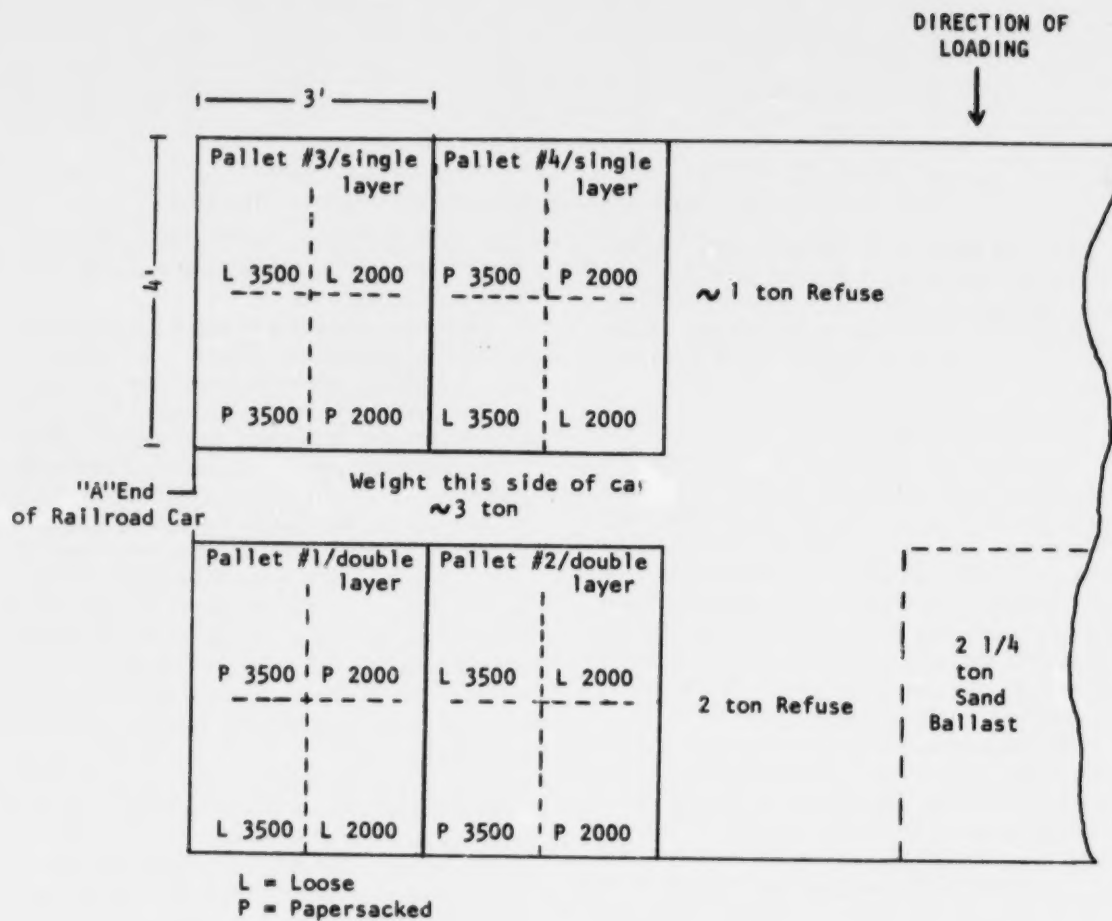
hours; and (c) Toledo - Cleveland, Ohio-3.0 hours. The remainder of the time was spent waiting or in classification yards.

During the more than 350-mile trip from Chicago to Cleveland, the test car registered two longitudinal impacts in Zone 3-exceeding accelerations of 6 miles per hour, which is considered rough handling. In addition, the test car sustained eight impacts in Zone 2. The distribution of the impacts was as shown in Table 44.

In evaluating the data in Table 44 it should be recalled, as outlined previously, that the probability of a car being struck at speeds exceeding 6 miles per hour is 1 in 3 if the car passes through three classification yards. Since the test car passed through three classification yards, the results suggest that the transport test conditions were, as requested, more severe than those encountered normally in railroad operations.

The over-the-road impacts which occur generally from the run-in and run-out of slack in the car coupling connections were all confined to Zone 1 during this test. This represents careful handling of the cargo in transport and results from proper train operation. No attempt was made to count the number of Zone 1 impacts sustained during the shipment.

The relationship of the longitudinal and vertical shocks is shown in a selection of tape sections given in Figure 25 on the following page. The tapes indicate that most vertical shocks result, as outlined previously, from longitudinal shocks. However, the vertical shocks are, as shown, of short duration. They generally last only for 0.01 seconds, while longitudinal



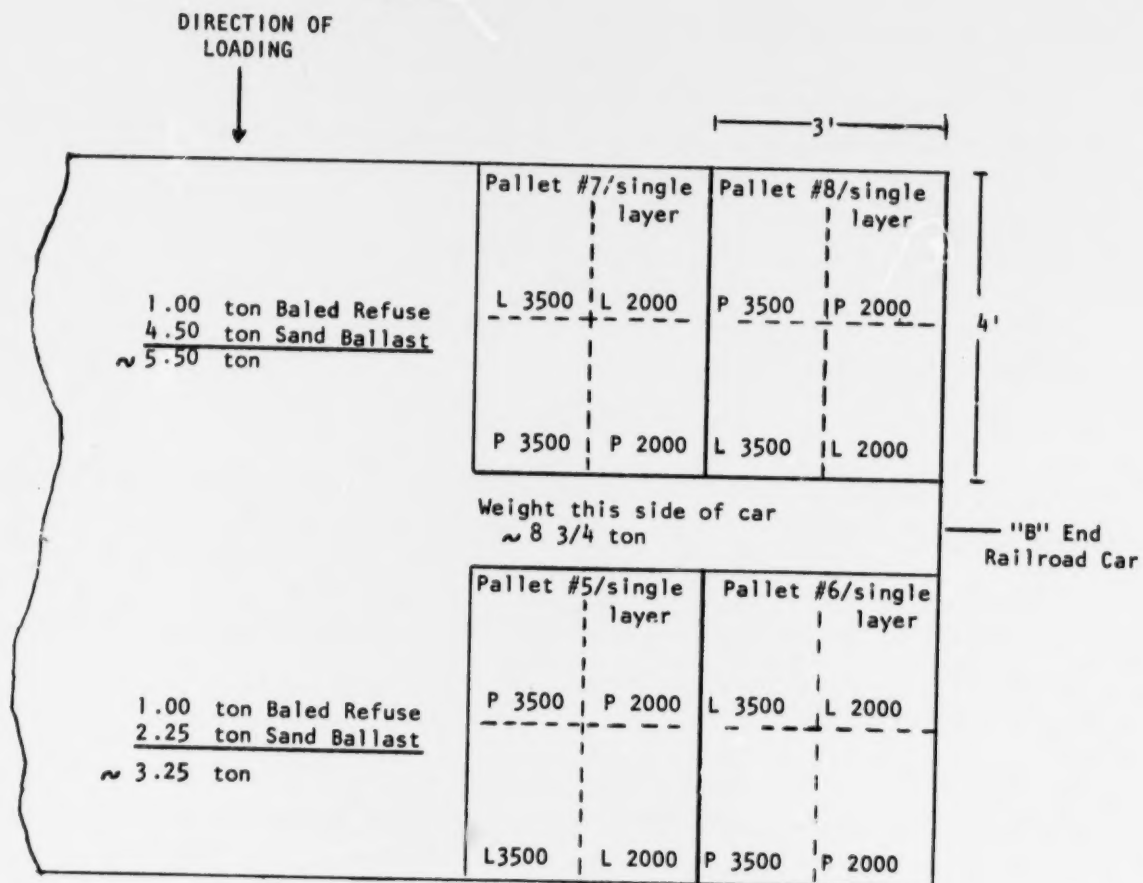
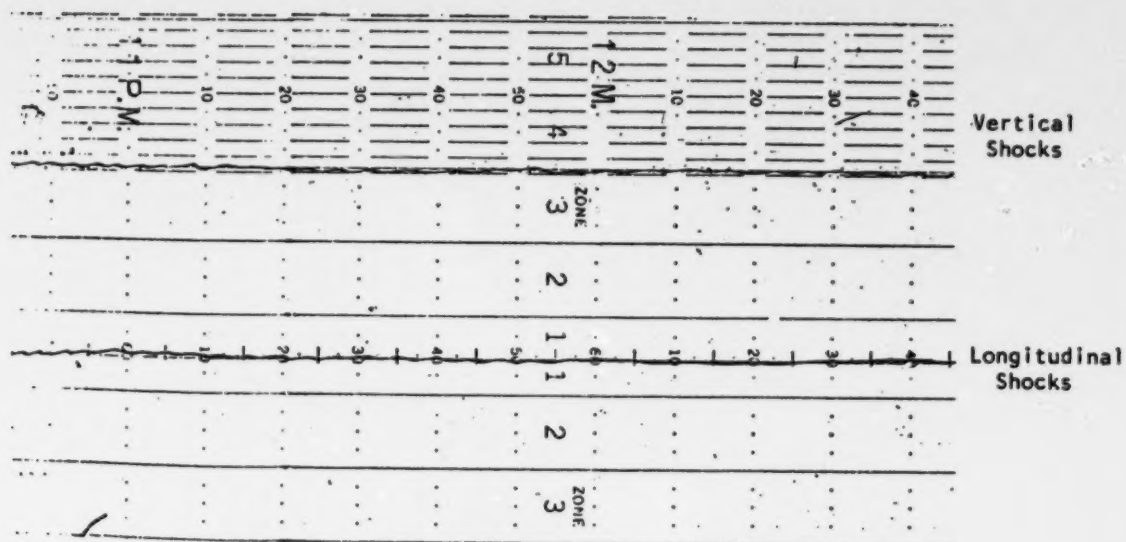
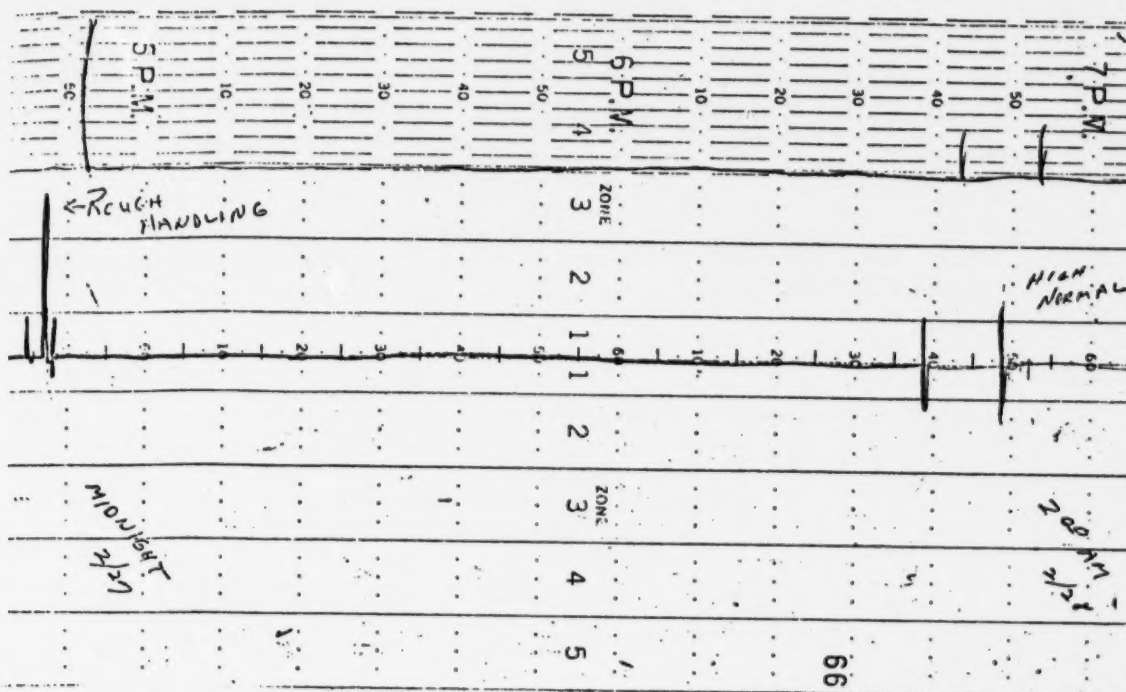


FIGURE 24
Illustration of the Bale Loading Configuration
Used in the First Rail Test Shipment

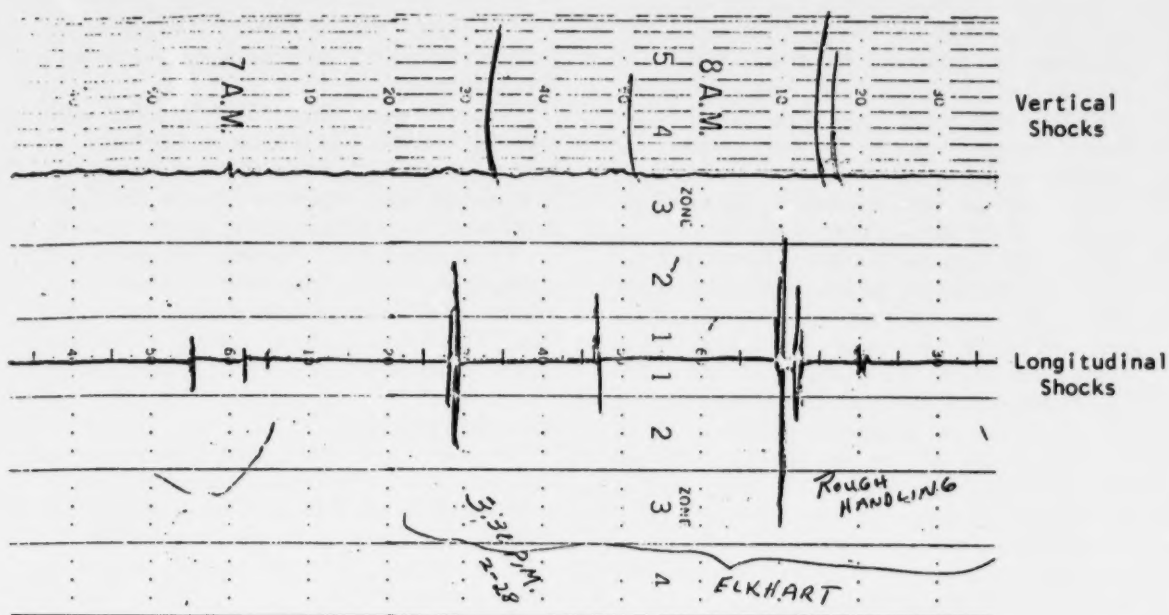


(1) Typical Over-the-Road Impact Recording

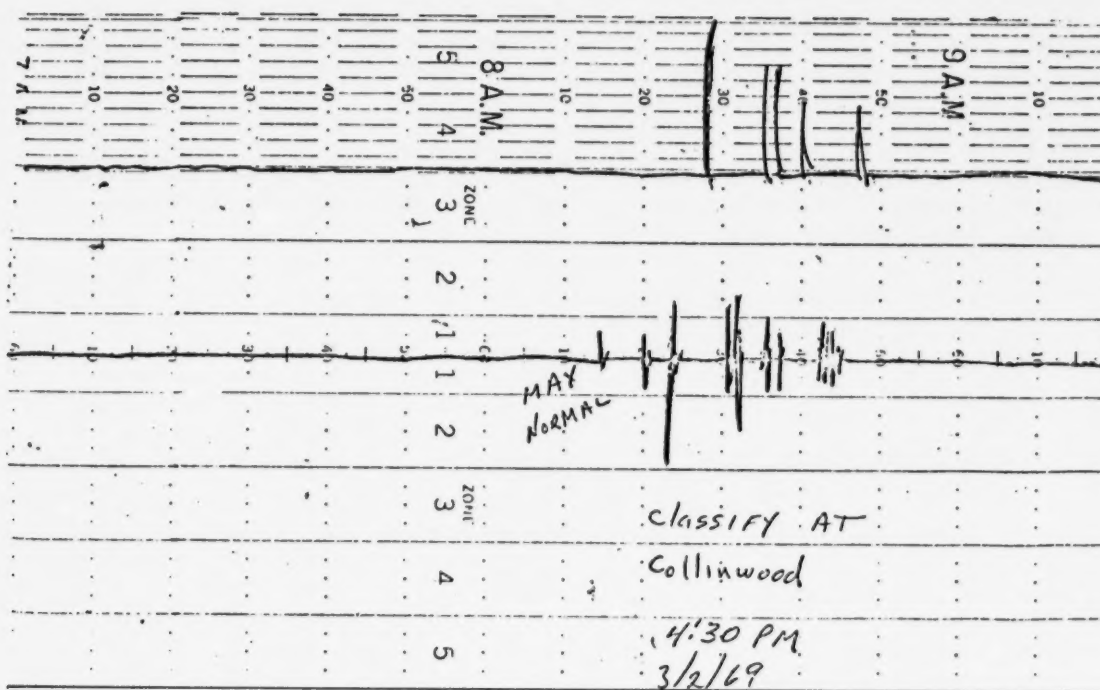


(2) Colehour Yard, Chicago, Illinois

FIGURE 25
Example of Impact Recordings Made During the First
Rail Test Shipment



(3) Elkhart, Indiana



(4) Collinwood Yard, Cleveland, Ohio

FIGURE 25
Examples of Impact Recordings Made During the First
Rail Test Shipment

shocks last, as a rule, for 0.1 seconds. The tapes show that the vertical shocks were quite severe.

The car was first inspected in Elkhart, Ind., before it was humped in the classification yard. The bulkheads and bracing were found to be broken and the bales had shifted a few feet. Also, a part of the sandbag loading ballast had been dislodged and thrown throughout the car. No bale, however, was destroyed or broken.

The car was again inspected in Cleveland by members of the research staff of the Penn Central Railroad. The cargo had not shifted further than was observed at Elkhart. All the bales were found in good condition; not one bale had disintegrated or crumpled. Some bales were steaming and their outside temperature was estimated at 90 to 100 degrees Fahrenheit. The ambient temperature during the trip was between 25 and 40 degrees F.

Subsequently, the car was rerouted to Chicago for a final inspection of the bales. Impact measurements were not taken during the return trip which again required from 2 1/2 to 3 days in time. An unknown number of additional impacts were sustained by the test car during this trip.

The final inspection was made in Chicago by members of the project team. It indicated that none of the bales were destroyed. Even the two second-layer front bales from Pallet No. 2 which had fallen off and been thrown around in the car were only partially damaged. All the other bales were judged to be in very good, or at the very least, still in acceptable condition.

Furthermore, all the bales that were weighted down by either sandbags or other bales appeared to be in better condition than the bales not weighted

down. This corresponds to the loading experience gained from other rail shipments and reported at the beginning of this section. It indicates that a reasonably tight and confined loading reduces the negative effects of impact and vibration generated during transport.

The bales made from refuse in paper sacks appeared, as a rule, to be in better condition than the bales made from loose refuse. Only one paper-sacked bale showed some separation between the sacks; nonetheless, it was judged to be in "good" condition.

Finally, there was a relatively small amount of spillage from the bales made from loose refuse. It is estimated that the total spillage amounted to less than 50 pounds or less than 1 percent of the total weight of these bales. There was no spillage from the paper-sack bales.

III. CONCLUSIONS

The above test results support the conclusion that solid waste bales made from either loose or paper-sacked refuse were extremely stable. All the bales shipped appeared to exceed substantially the stability required by most rail-haul systems as currently contemplated.

It must be remembered in this context that additional impacts of an unknown number and magnitude were undoubtedly sustained during the return trip of the test car from Cleveland to Chicago. Considering the final results of this test, this fact can only strengthen the certainty of the conclusions drawn.

A selected number of the pictures taken during the first rail shipment test are reproduced on the following pages. The pictures show the test setup as well as the condition of the bales after their return to Chicago.

TABLE 44
Incidence of Longitudinal Impacts on Test Car During Transport
of Bales from Chicago to Cleveland in First Rail Test Shipment

Location of Impact Occurrence	Number and Strength of Impacts		
	Normal Yard Operation	Rough Handling	Severe Handling
	Zone 2	Zone 3	Zone 4
Colehour Yard	1	1	0
Colehour Yard to Elkhart	0	0	0
Elkhart Yard	3	1	0
Elkhart to Toledo	0	0	0
Toledo area	1	0	0
Toledo to Collinwood, Cleveland	0	0	0
Collinwood Yard & area	3	0	0



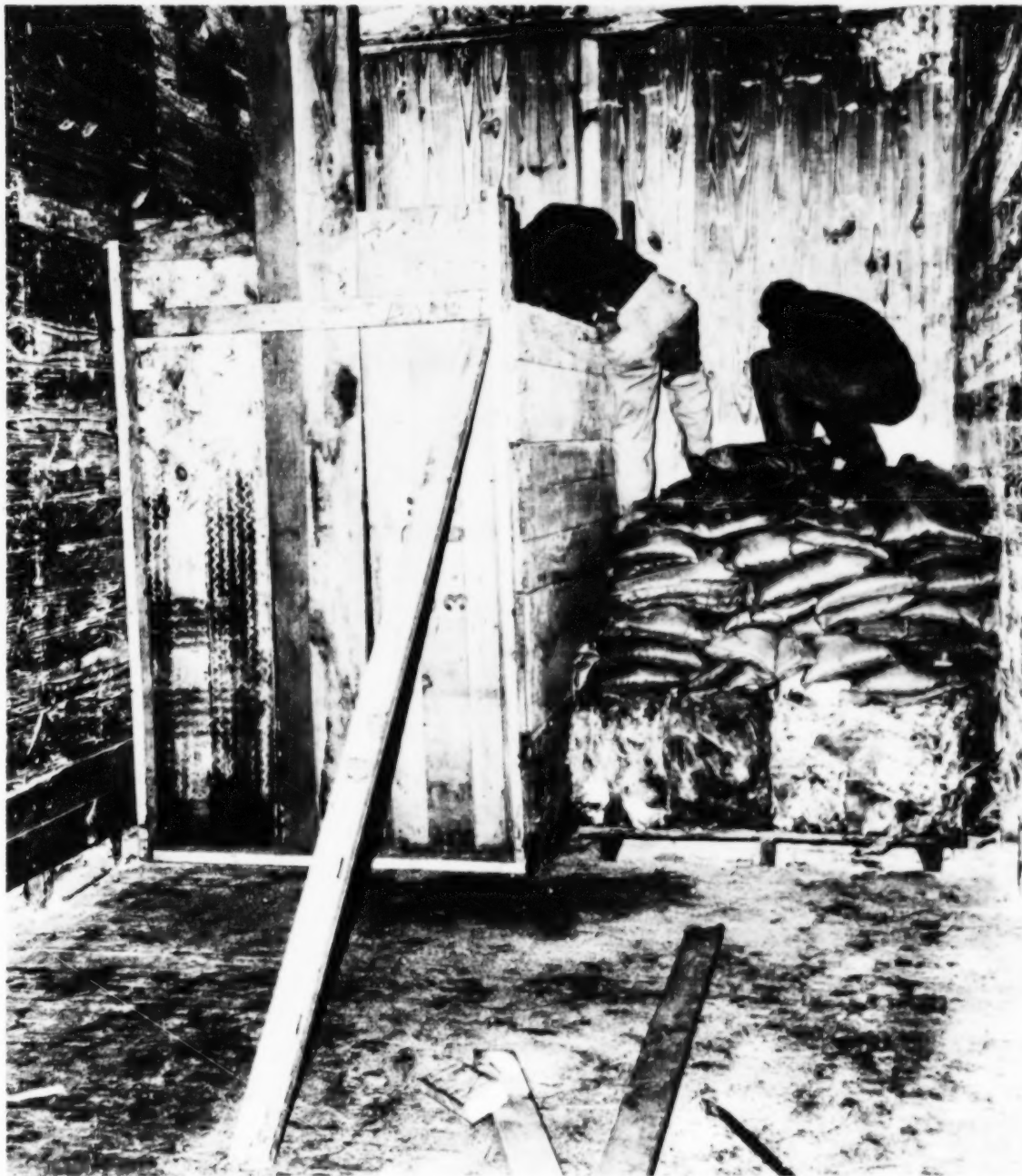
(48)

The boxcar used for the first rail test shipment



(49)

Bales loaded down with sandbags . two tons of sand per square yard left and one ton per square yard right



(50)

Bracing of the Bales Before Shipment:
(50) Bales Loaded Down with Sandbags



(51)

Bracing of the Bales Before Shipment:
(51) Bales not loaded down



(52)

Condition of the load after return to Chicago. Light line in left corner indicates height of sandbag pile.



(53)

Condition of weighed down bales after return to Chicago. Notice small amount of spillage. Bales have expanded to fill voids left by stacking.



(54)

Condition of bales not weighed down after return to Chicago. Notice small amount of spillage.



(55)

Bales on truck after unloading of test car in Chicago. Notice condition of bales after more than 700 miles of rail transport.

SECTION FIVE—SECOND 700 MILE RAIL TEST SHIPMENT INVOLVING 264 BALES WITH SELECTED CHARACTERISTICS

The second and last rail test shipment made with respect to this, as well as the APWA rail-haul project, was designed to simulate actual solid-waste-rail-haul shipment conditions as close as possible.

Specific credit must be given to the City of Chicago, a participant in the APWA rail-haul project, which enabled the project team to execute this vital test, which might be considered the heart of the stability investigations.

Without this second rail shipment test it could be possible to judge all the previously reported stability test results as being more indicative than definitive.

I. THE TEST SETUP

The second rail shipment test was set up in a way similar to the first rail shipment test. With the exception of a greatly enlarged scale, a similar combination of transport factors were taken into account.

1. Rail Equipment, Transport Distance and Route

The bales were loaded again on a boxcar. However this car was 50 feet long, 9.2 feet wide, and 10.6 feet high. The car was again moved by regular freight trains and covered the same distance and route as the first test car.

In addition to an impact recorder mounted on a side wall, the car was also equipped with a humidity and a temperature recorder.

2. The Bale Sample

As shown in Table 45 on the following page, the 264-bale sample was again structured to contain an equal number of bales made from loose household refuse and from household refuse placed in paper sacks before compaction.

Furthermore, each of these two groups was made up of a substantial number of bales compacted at gauge pressures of about 2,500, 2,000 and 1,500 psi. The results of compaction experiments conducted just prior to the second shipment test had indicated that compaction at pressures in the range from 1,500 to 2,500 psi might produce significant over-all system advantages.

Finally, each subgroup of samples was set up to include bales of varying ages. Approximately 24 percent of the bales were more than 8 days old, about 48 percent were more than 7 days old and about 71 percent were more than 6 days old at the outset of the test shipment. Correspondingly only 29 percent of the bales were less than 6 days old and 52 percent less than 7 days old. The variations in bale age were

introduced to gauge the operational flexibility that a solid-waste-rail-haul system might be able to afford with respect to bale pickup schedules.

3. The Loading Configuration

All 264 bales were stacked on pallets in four columns stacked four high, totaling 16 bales per pallet. Each stack of four bales consisted primarily of bales having approximately the same characteristics, e.g., four bales made from refuse placed in paper sacks before compaction and compressed at 1,500 psi, or four bales made from loose refuse and compressed at 2,000 psi, etc.

As shown in Table 46, the average weight of all the bales is calculated to be 183 pounds. The average weight of the bales calculated per pallet varied from 167.5 to 213.5 pounds. This implies that the bottom of the lowest bale carried a load of about 670 to 855 pounds under static conditions and a higher load under dynamic conditions.

The pallets were loaded randomly at both ends of the car. The first eight pallets were placed at one end and the other nine pallets at the other end of the car. The loads at both ends were again secured by bulkheads and bracing.

II. THE TEST EXECUTION AND RESULTS

Just as in the first transport test, the car was again 2 1/2 to 3 days enroute from Chicago to Cleveland. However, this time the actual transit time amounted to about 14.5 hours: Chicago to Elkhart, Indiana, 5.5 hours; Elkhart to Toledo, Ohio, 5 hours; and Toledo to Cleveland, Ohio, 4 hours.

During its more than 350-mile trip from Chicago to Cleveland, the car registered one impact in Zone 4 which, exceeding 8 miles per hour, is considered severe rough handling. The specific distribution and severity of the longitudinal impacts was as shown in Table 47.

It might be recalled from the previous discussion that the probability of a car being struck at impact speeds exceeding 8 miles per hour is only 1 in 20 if the car is handled in three railroad yards. Considering that impacts occurred in Zone 3 as well as Zone 4, this test was fortunate in encountering transport conditions more severe than those experienced in the first rail test shipment. Thus, the test results must be judged to be even more impressive than those obtained previously.

Again the car was inspected in Cleveland by members of the research staff of the Penn Central Railroad. The bulkheads on one end of the car had collapsed and some bales had spilled into the center of the car. The bulkheads at the other end of the car were damaged. However, all the bales were found to be in good condition; not one bale had disintegrated.

TABLE 45

Summary of Selected Information on the 264 Bales
Subjected to the Second Rail Transport Test Covering
a Travel Distance of More than 700 Miles

DAY 6 DATE/ Bale Pro- duction REFUSE COMPACTED	WEATHER CONDITIONS	BREAKDOWN OF NUMBER OF BALES WITH RESPECT TO APPLIED PRESSURE AND TYPE OF BALE									
		2500 PSI GAUGE PRESSURE		2000 PSI GAUGE PRESSURE		1500 PSI GAUGE PRESSURE		TOTAL NUMBER OF BALES		APPROXIMATE AGE OF BALES	
		Loose No. of Bales	Paper- sacked No. of Bales	Loose No. of Bales	Paper- sacked No. of Bales	Loose No. of Bales	Paper- sacked No. of Bales	Loose	Paper- sacked Total	Before Shipment to Cleveland (5/8/69)	After Return from Cleveland (5/15/69)
Tues. 4/29/69	Household Refuse (Chicago) includ- ing about 20% yard rakings (dirt, grass, weeds and leaves)	7	7	4	4	3	3	14	14	9	16
Wed. 4/30/69	Same										17
Thur. 5/1/69	Same	5	5	8	8	5	5	18	18	8	15
Fri. 5/2/69	Household Refuse Yard rakings about 5%	12	12	8	8	12	12	32	32	7	14
Mon. 5/5/69	Household Refuse No yard rakings	8	8	12	12	12	12	32	32	6	13
Tues. 5/6/69	Household Refuse 20% yard rakings including tree branches	4	4	6	6	2	2	12	12	3	10
Wed. 5/7/69	Same, wet	4	4	2	2	6	6	12	12	2	9
	TOTAL	44	44	46	46	42	42	132	132	5.74 Average	12.74 Average

TABLE 46
Weight of Bales Shipped in the Second Rail Transport Test

PALLET NUMBER	TOTAL WEIGHT of Bales (16 units per pallet)	AVERAGE WEIGHT per Bale
	(pounds)	(pounds)
1	3420	213.75
2	2920	182.50
3	3000	187.50
4	3220	201.25
5	3160	197.50
6	3120	195.00
7	2720	170.00
8	3020	188.75
9	2680	167.50
10	2840	177.50
11	2740	171.25
12	3100	193.75
13	2820	176.25
14	2780	173.75
15	2780	173.75
16	2840	177.50
17	<u>1380</u> (8 bales)	<u>172.50</u>
	TOTAL 48,540	183.86

TABLE 47
Incidence of Longitudinal Impacts on Test Car During Transport
of Bales from Chicago to Cleveland in Second Rail Test Shipment

Location of Impact Occurrences	Number and Strength of Impacts		
	Normal Yard Operation	Rough Handling	Severe Handling
	Zone 2	Zone 3	Zone 4
Colehour Yard	0	0	0
Colehour Yard-Elkhart	0	0	0
Elkhart Yard	1	0	0
Elkhart-Toledo	0	0	0
Toledo Area	0	0	0
Toledo-Cleveland	0	0	0
Collinwood Area	1	1	1

Source: Technical Center, Penn Central Railroad

The humidity indicator functioned for only about 19 hours, i.e., until the ink was knocked from the marking pen, apparently by coupling impacts. The chart showed that the relative humidity rose within the closed car from 85 percent to 100 percent within 2 1/2 hours after the loading was completed. The humidity then remained at 100 percent for the remainder of the recorded time. It should be noted, however, that it rained during the early part of the shipment.

The temperature chart, as shown in Figure 26, registered some high frequency pen vibrations caused by car body motion. Ignoring these vibrations, the chart shows that the car air temperature ranged from 70 degrees to 95 degrees Fahrenheit. Temperature maxima were registered just after noon of each of the 5 days of record-taking.

To put the temperature and humidity data into some perspective, it is necessary to consider the weather conditions prevailing in the total test area during the test period. The general temperature and

humidity readings for Chicago and Cleveland were as shown in Table 48.

In analyzing the data in Table 48 it must be recognized that the bale production for this test started on April 28, 1969 and that the transport movement itself began in the afternoon of May 8, 1969. A general comparison between the measurements taken inside the test car and those established by the U.S. Weather Bureau indicates that the bales produced a significant amount of both heat and moisture. These findings indicate that some degradation of the organic constituents of the bales took place during transport and that the decomposition was most likely aerobic.

The data, however, do not lend themselves to a quantitative evaluation of the biological activity in the bales. Furthermore, these data are not, by themselves, adequate for the establishment of quantitative inferences concerning all the rail-car and transport requirements. Factors such as the type of car and car enclosure, the tightness of the doors, the

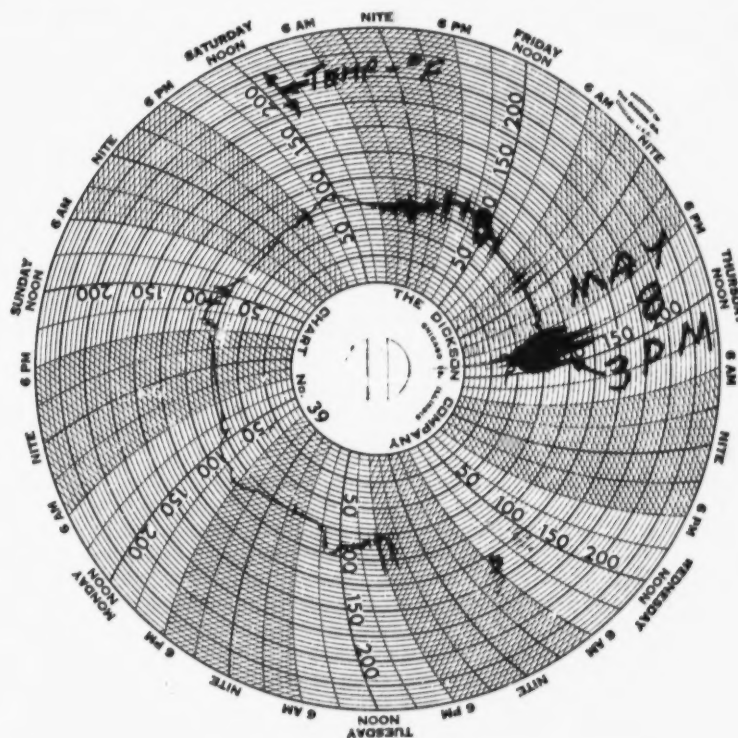


FIGURE 26

Record of Air Temperature in the Test Car
During the Second Rail Test Shipment

Source: Champ Carry Technical Center, Pullman Standard,
Division of Pullman, Incorporated

cooling effects of prevailing winds, and the air speed during transport, would need further investigation. Nevertheless, the available data can be considered a good indicator of some significant conditions which must be recognized in the rail-haul of solid wastes. Combined with the total information developed during this project, the data are judged to provide a basis sufficient for the establishment of the initial specifications for rail-haul demonstration projects.

Finally, the return trip of the car from Cleveland to Chicago required again 2-1/2 to 3 days in time. Although impact measurements were not taken during that time, it is clear that impacts did occur. In the over-all, all bales again came back intact and the amount of spillage was estimated again at less than 1 percent of the weight of the loose bales.

III CONCLUSIONS

Considering the lading configuration, specifically the height of the lading, and the severe handling of the test car, railroad experts regard the test results as

adequate proof of the excellent stability of the compacted bales. In their judgment bales of type and kind tested will be acceptable for shipment by any railroad.

This conclusion was already reached by the rail shipment experts after completion of the shipment from Chicago to Cleveland. Since the bales remained intact even after the additional Cleveland-Chicago return trip, it is clear that the stability of the bales must be considered excellent indeed.

Finally, the bales are capable of developing a significant amount of heat and moisture during transport. This possibility must be taken into account in the selection of rail cars as well as in the establishment of bale storage facilities desired at the transfer station or the disposal site.

A selection of pictures taken during the second rail test shipment is presented on the following pages to convey, visually, the extraordinary stability shown by the bales used.

TABLE 48
Selection of Local Climatological Data for Chicago
Illinois and Cleveland, Ohio for Time Period
April 28, 1969 to May 15, 1969

Date	Chicago					Cleveland				
	Temperature		Humidity		Rainfall	Temperature		Humidity		Rainfall
	High	Low	High	Low		High	Low	Average		
1969	°F.	°F.	%	%	(inches)	°F.	°F.	%	%	(inches)
4/28	54	39	86	76	0.19					
4/29	51	36	76	36	0.00					
4/30	62	37	76	37	0.00					
5/1	73	47	71	31	-					
5/2	85	56	53	21	-					
5/3	82	54	77	42	T					
5/4	83	56	72	29	T					
5/5	79	62	67	45	T					
5/6	81	65	84	44	.06					
5/7	76	57	87	37	.28					
5/8	70	51	86	51	.48	79	54	58		.76
5/9	58	47	86	53	.28	56	38	43		.17
5/10	52	42	86	54	.58	54	38	43		.62
5/11	58	42	73	38	.08	53	39	35		.36
5/12	63	40	82	34	T	55	39	36		.00
5/13	67	45	86	50	0.00	68	39	40		.02
5/14	73	49	93	30	0.00	64	47	41		T
5/15	79	52	74	45	T	67	39	38		.00

T = Thunderstorm

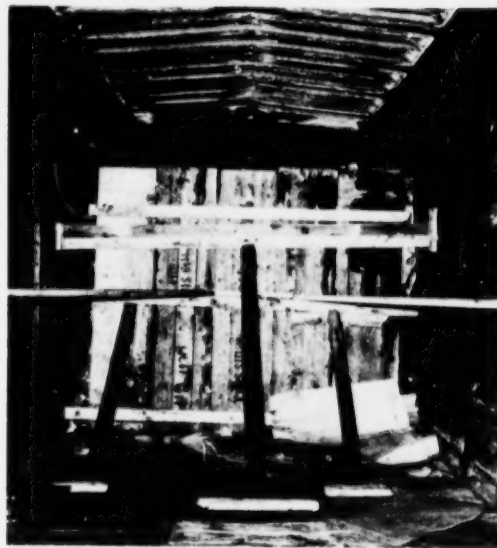
Source: U. S. Department of Commerce, Weather Bureau



(56)



(57)

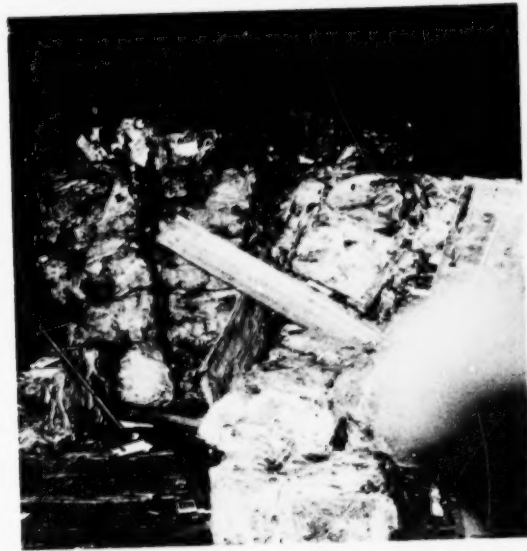


(58)

Bales before the second, more than 700 mile rail test shipment. Notice space left due to stacking on pallets which causes instability of the load and therewith more severe test conditions.



(59)



(60)



(61)

Condition of load after return to Chicago in second rail test shipment.



(62)



(63)



(64)

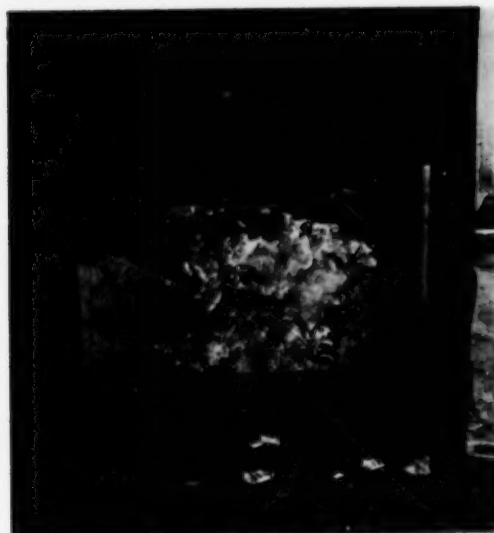


(65)

Condition of load after return to Chicago. Notice small amount of spillage. Paper-sacked refuse bales appear to be in excellent condition.



(66)



(67)



(68)

- (66) Loose Refuse Bales Survived the Test Quite Well.
- (67) Unloading of Loose Refuse Bale.
- (68) Unloading of Bales, Notice Form of Bales Left After Rough Unloading Procedure.

SECTION SIX—THE DROP TEST SERIES COVERING, IN 18 TESTS, 46 BALES WITH VARYING CHARACTERISTICS

Although the vibration and impact tests showed that the solid waste bales were extremely stable, it was decided to conduct a series of drop tests in order to augment the available information on the structural stability of the bales. The drop test were made either at the test site or at the Idea Center of Acme Products Division of Interlake Steel Corporation.

In total, 46 bales were selected at random and subjected to drop tests in 18 separate test operations. The major test variables concerned (a) bale characteristics, in particular bale age; (b) the height and number of drops; and (c) operationally oriented drop conditions such as the number of bales dropped simultaneously. The individual bale and test characteristics and the test results are summarized in Table 49 presented on the following pages.

In evaluating the data in Table 49 it should be highlighted that the height of the drop amounted usually to about 9 or 10 feet. Only two drops were made from a height of 5 feet. Although it is not anticipated that rail-haul systems will be designed to require dropping of the bales in regular operations it must be recognized that drops might occur accidentally.

In the overall, the drop test results complement the findings presented previously on the other stability tests. Solid waste bales, which appear stable after exit from the press, are capable of taking a considerable beating from drop impacts. This holds true regardless of whether the bales are dropped individually or in groups. However, it appears that bales produced at higher compaction pressures are more resistant to drop impacts than, as expected, bales produced at low compaction pressures.

The drop tests confirm on their own and in their own way all the conclusions drawn previously. Solid waste bales which appear to be acceptable after leaving the compaction press will also meet all the stability requirements of currently contemplated rail-haul systems.

A selection of pictures taken during the drop tests is given on the following pages.

SECTION SEVEN—OBSERVATION OF BALE PROPERTIES DURING THE NUMEROUS BALE—HANDLING OPERATIONS REQUIRED AT THE TEST SITE

The operations at the test site required that each bale be handled many times. Specifically, each bale had to be (a) removed from the press after

compaction, (b) transported to the scale in the bucket of a front-end loader, (c) placed on the scale and removed after weighing, (d) transported again in a front-end loader to an interim storage place inside the building, and there (e) put on the floor of the building or on a table. In addition, the test operations often required that the bales be shifted around within the building so as not to interfere with the experiments going on.

Moreover most bales were transported to the outside of the test building and stored there for a considerable length of time for observation. Observations of bale appearance and stability and attempts to manually remove apparently loose portions of the surfaces and corners, were made at random throughout the test period.

The numerous observations throughout the 10-week test period can be summarized as follows:

1. Bales that appear cohesive after exit from the press can be handled without special precautions.
2. Even bales exhibiting apparently significant structural defects are still surprisingly strong in terms of the bale handling operations performed.
3. Exposure of bales for about three weeks to outside weather conditions during February to May 1969, did not cause an appreciable or obvious amount of structural deterioration.
4. Spillage, as a rule, amounted to less than 1 percent of the weight of the bale.

The above observations, although not documentable in terms of specific measurements, are presented to enhance the test results given on bale stability. In combination with the findings presented previously, they support the conclusion that bale handling needed at the transfer station, will not be a source of significant difficulties.

SECTION EIGHT—MAJOR CONCLUSIONS ON THE STABILITY OF COMPACTED SOLID WASTE BALES

A highly significant number of bales produced during this test program and representing a great variety of bale characteristics were subjected to a broad series of relatively severe stability tests.

The test results, taken in combination, indicate that solid waste bales are surprisingly stable. Bale failure under test conditions which surpassed substantially all the current requirements for solid-waste rail-haul was extremely rare.

Bales produced at compaction pressures in the range from about 2,000 to 3,500 psi did not appear to require special care with respect to rail transport or material handling. In the over-all, bales made at these

pressures from either loose or shredded refuse or from refuse placed in paper sacks performed exceedingly well.

Finally, as indicated in Section One of this chapter, the bales subjected to the tests must be considered, for practical purposes, as being at equilibrium with respect to their internal cohesive and expansive forces. Most of the springback activity,

which occurs within the first 5 minutes after bale exit from the press, had already taken place in some cases, long before any of the stability tests were made.

Thus, it can be concluded that solid waste bales exhibiting a stable appearance after exit from the press are, as a rule, suitable for the transport and material handling operations of rail-haul systems as currently contemplated.

Table 49. Summary of Drop Test Results

Test Characteristics and Observations	Test Number 1	Test Number 2	Test Number 3	Test Number 4	Test Number 5	Test Number 6	Test Number 7	Test Number 8	Test Number 9
1. Number of Bales Involved	2	1	4	2	1	1	1	1	1
2. Bale Characteristics	Chicago, Illinois Watered down (dripping) Household Refuse	Same as before	Madison, Wisconsin Household Refuse	Madison, Wisconsin Household Refuse	Same as before	Same as before	Madison, Wisconsin Household Refuse	Chicago, Illinois Household Refuse	Same as before
a) Bale material	LOOSE	"	SHREDDED	SHREDDED	"	"	SHREDDED	LOOSE	"
b) Production parameters	3500 psi	Same as before	3500 psi	3500 psi	Same as before	Same as before	3500 psi	3500 psi	3500 psi
ba) Compaction Pressure (gauge psi)	none	"	none	none	"	"	strapped	none	strapped
bb) Fertilization	one hour	"	two hours	two hours	one day	Same as before	one day	one day	one day
c) Condition	none	"	none	none	Same as before	"	none	none	none
ca) Age, approx.	10 feet	"	10 feet	10 feet	12 feet	9 feet	9 feet	Same as before	Same as before
cb) Participation in previous stability tests	1	"	1	1	1	2	2	1	2
3. Drop Characteristics	Bale tumbled	"	Smooth	Smooth	Same as before	Same as before	Smooth	Tumbling	Smooth
Height of Drop									
Number of Drops									
Description of Drop									
4. Condition of Bale AFTER Drop	Good, bales hold together well	Same as before	Very Good	Very Good	Very Good	Good	Good, Strapping held well	Poor	Good
Overall Bale Evaluation	Spillage from edges	Same as before	One bale showed crack in the middle	One bale developed a crack at corner, corner could be removed easily	Slight deterioration of a small part of the surface	Some spillage, otherwise good	One corner fell off; however, major portion held well	Originally poor bale; appreciably damaged after drop, suitable for only one drop	Originally good bale; remained good after drop
Special Defects									

Table 49 (continued) Summary of Drop Test Results

Test Characteristics and Observations	Test Number 10	Test Number 11	Test Number 12	Test Number 13	Test Number 14	Test Number 15	Test Number 16	Test Number 17	Test Number 18
1. Number of Bales Involved	1	1	4	6	4	4	4	4	4
2. Bale Characteristics									
a) Bale material	Chicago, Illinois Household Refuse PAPERSACKED	Same as before	Chicago, Illinois Household Refuse LOOSE AND PAPERSACKED	Chicago, Illinois Household Refuse LOOSE AND PAPERSACKED	Chicago, Illinois Household Refuse Same as before	Chicago, Illinois Household Refuse Same as before	Chicago, Illinois Household Refuse LOOSE AND PAPERSACKED	Same as before	Same as before
b) Production parameters									
ba) Compression	3500 psi	3500 psi	2000 and 3500 psi	2000 and 3500 psi	Same as before	Same as before	2000 and 3500 psi	Same as before	Same as before
bb) Fortification	none	strapped	none	Strapped loosely in bales of three	none	"	none	"	"
c) Condition									
ca) Age, approx.	one day	Same as before	14 to 17 days	14 to 17 days	Same as before	Same as before	14 to 17 days	"	"
cb) Participation in previous stability tests	none	"	After 1st Rail Shipment Test	After 1st Rail Shipment Test	"	"	After 1st Rail Shipment Test	"	"
3. Drop Characteristics									
Height of Drop	9 feet	Same as before	5 feet	5 feet	10 feet	Same as before	10 feet	Same as before	Same as before
Number of Drops	2	"	1	1	1	"	1	"	"
Description of Drop	Smooth	Smooth	Rough	Rugged	Same as before	Same as before	Rugged	"	"
4. Condition of Bale AFTER Drop									
Overall Bale Evaluation	Fair	Good	Loose 2000 psi; disintegrated; Loose 3500 psi; good. Papersacked 2000 psi and 3500 psi; disintegrated at paper sack interfaces	Good	3 bales good	Loose 2000 psi; disintegrated	Loose 2000 psi; partially disintegrated; Loose 3500 psi; good. Papersacked 2000 psi; partially disintegrated	All bales good	Loose 2000 psi; disintegrated
Special Defects	Loosening at interfaces of bags though bales could be picked up; original bale had already definite cracks at bag interfaces	Some spillage from one side of torn papersack		All bales held together, some straps broke	Loose 2000 psi, partly disintegrated				Loose 3500 psi; good. Papersacked 2000 psi; poor. Papersacked 3500 psi; fair

TESTS NO. 9 AND NO. 8
 CONSISTENCY - SHREDDED
 STRAPPING - TEST NO. 9 - NONE
 TEST NO. 8 - 5/8 x .020 inches



After Two Drops

TESTS NO. 10 AND NO. 12
 CONSISTENCY - HOUSEHOLD LOOSE
 STRAPPING - TEST NO. 10 - NONE
 TEST NO. 12 - 5/8 x .020 inches



After One Drop



After Two Drops

TESTS NO. 13 AND NO. 11
CONSISTENCY - HOUSEHOLD IN PAPER SACKS
STRAPPING - TEST NO. 13 - NONE
TEST NO. 11 - 5/8 x .020 inches



After Two Drops

CHAPTER V

THE IMPLICATIONS OF APPLYING HIGH PRESSURE COMPACTION TO SOLID WASTES FOR RAIL-HAUL AND SOLID WASTE DISPOSAL

This chapter takes up the implications of applying high pressure compaction to solid wastes for rail-haul as they relate to the development of suitable compaction equipment and major rail-haul system building blocks. As outlined in the APWA rail-haul interim report, the major building blocks of the system are (1) the transfer stations, (2) the transport link, and (3) the sanitary landfills.

In analyzing these implications, it must be recognized that they are to be dimensioned within the scope of two different projects. This report emphasizes the compaction-oriented implications. The report on the first phase of the rail-haul feasibility study deals in detail with the rail-haul system implications.

The high pressure compaction of solid wastes is expected to have implications far beyond the scope of solid-waste rail-haul. Thus, to put the results of this project into some perspective in terms of total solid waste disposal problem, it was considered appropriate to indicate some of the non-rail-haul implications and promises as well.

SECTION ONE—THE DEVELOPMENT OF COMPACTION EQUIPMENT PERFORMANCE SPECIFICATIONS

Acceptable equipment performance specifications have to be reasonable in terms of the technical requirements as well as the cost incurred in meeting those requirements. Today's technology has demonstrated quite clearly that almost any technical objective can be achieved if cost, relative economics, and allocation of resources are not restraints. However, to develop compaction equipment specifications for the reality of solid wastes disposal, which is quite sensitive to costs, it was necessary to keep in mind the cost-performance factors associated with alternative specifications. In terms of compaction technology, this implies that attention should be given the low pressures of a given pressure range, to a reasonable size of the bale in the compaction chamber, to a low weight/force ratio of the press frame, to machinery requirements, and to cycle speeds and sequences.

To perform the investigations concerned in a reasonable manner requires the establishment of criteria for a comparison of different compaction

press systems. Unfortunately a comprehensive comparison represents an undertaking far beyond the limited scope of this project. It must be highlighted in this context that an investigation of alternate press performance specifications necessitates many analyses of numerous relationships between a large number of variables which are, in themselves, extremely complex.

Thus, the decision had to be made to confine the project efforts in this area to tentative, exploratory investigations aimed at the development of indicative rather than definitive guideline information.

I. GUIDELINES FOR THE INVESTIGATION OF ALTERNATE COMPACTION EQUIPMENT SPECIFICATIONS

To guide and also to confine the study team efforts within the scope of available resources, it was necessary at the outset to establish selected constraints. To meet the project deadlines, however, these constraints had to be fixed before completion of the compaction experiments. Thus, the guidelines had to cover the problem of performance specifications in broad terms.

The specific guidelines used for this part of the study effort were as follows:

Characteristics of the material:

Heterogeneous mixtures of varying moisture contents which could behave like semi-solids under compaction, and exhibit springback characteristics instantaneously after release of pressure

Moisture content:

20 to 40 percent by weight of the input material mixture

Precompaction of input materials:

No precompaction of input materials other than that produced by collection trucks of the type now commonly used by municipalities.

Productivity

50 to 1,000 tons of solid waste per 8-hour shift

Cycle operating rate:

0.3 to 2.0 bales per minute, excluding any holding time of the final pressure applied

Total cycle rate:

Cycle operating rate plus a maximum of one minute of final pressure holding time

Compaction pressure applied:

2,000 to 3,500 psi without holding time, 2,000 psi and below with a maximum final pressure hold time of 1 minute

Material density in the compaction chamber:

Range of 70 to 90 pounds per cubic foot, average 1 ton per cubic yard (74 lbs/cuft)

Volume reduction ratio:

At least 15:1, preferably 18:1

Bale shape in the compaction chamber:

Cubic, rectangular or cylindrical

Bale size in the compaction chamber:

0.25 or 0.3 to 1.0 cubic yard

Stability of the bale:

Except for bales made from refuse delivered during heavy rains, almost all bales are stable after release of pressure

Basic process operations:

Uninterrupted, separate processing of each individual input charge regardless of the number of compaction stages. One bale is always produced per run from a single solid waste input load charged in one step

Feeding:

A full charge always fed into the charging box, no additional feedings of input materials during individual compaction runs

Type of compaction equipment:

Hydraulic presses

Useful service life of the equipment:

10 to 20 years at 5 days per week and 6 to 8 hours per day

Equipment cost:

Low-cost application of existing compaction technology is of key importance

In evaluating these guidelines plus the findings of the subsequent investigations, it must be stressed that they purpose to deal only with a very preliminary, conceptual value-engineering analysis. It should be recognized in this context that: (a) The design of existing metal scrap balers is often estimated to cost about 3,000 hours of engineering; (b) the design of completely new types of equipment requires more and perhaps different effort, and (c) the task at hand had to be tailored to the resources available.

It is obvious, of course, that the guidelines could be enlarged in number and be more detailed or stringent in content. It also is obvious that further work in equipment development, will modify the constraints and will elicit results which this project can only hypothesize.

Finally, to be on the safe side, it was decided to set some constraints to exceed the performance

specifications outlined in Chapter II of this report. As a result, the investigation of high pressure compaction for the rail-haul of solid wastes also provides information which points to potential applications in other phases of the solid waste disposal field.

II. PRESS CAPACITY CONSIDERATIONS

The constraints influencing the press capacity are interdependent. The press capacity is determined by the interrelationship between the total throughput tonnage, the bale size, and material density in the compaction chamber, and the rate of bale production.

1. Press Productivity in Terms of the Interrelationship Between the Bale Size and Material Density in the Compaction Chamber and the Rate of Bale Production

The interrelationship between throughput, bale size, material density, and rate of bale production is shown graphically in Figure 27. Both the total tons of waste compacted, as well as the number of tons handled per minute, are shown together on one axis and the number of bales per minute on the other axis. The relationship between bale size and bale weight in the compaction chamber was set for 1 ton to equal 1 cubic yard.

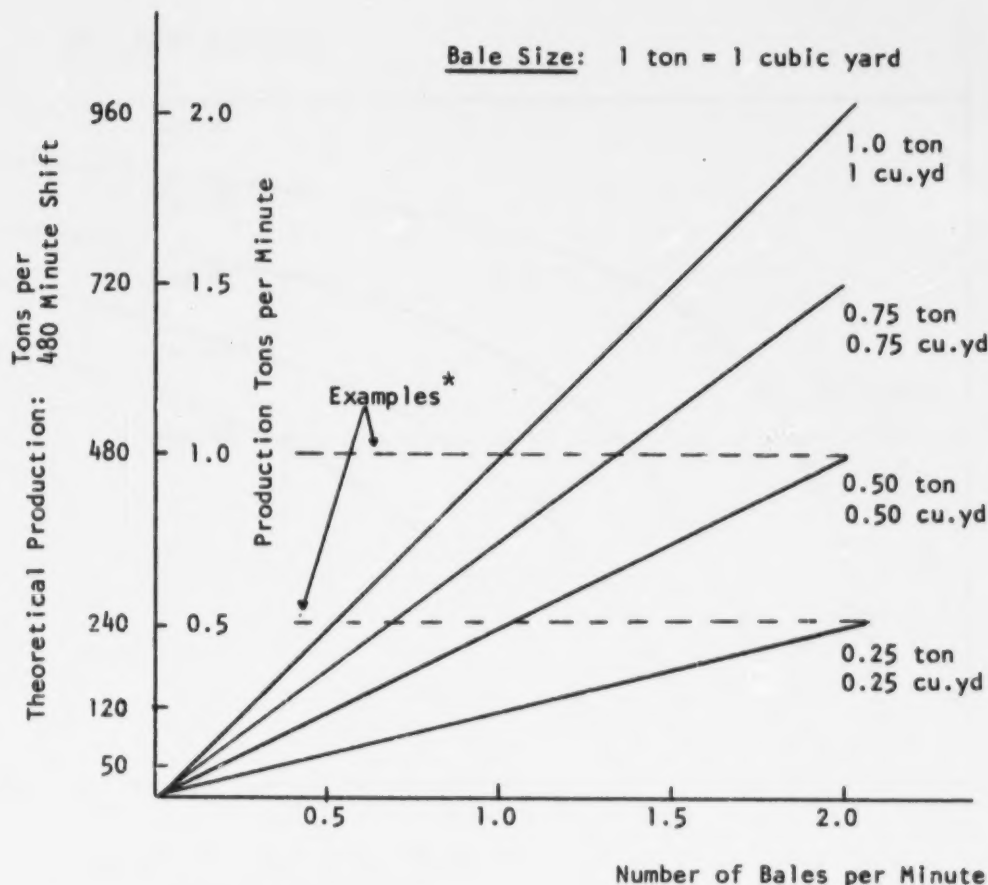
Figure 27 can be regarded as a graphic matrix for determining some of the specification alternatives resulting, not only from variations in the over-all production rate, but from tradeoffs between bale size and production rate. A 240-ton over-all throughput, for example, can be achieved with two 0.25-cubic yard bales per minute, one 0.50-cubic yard bale per minute, or one 1.0-cubic yard bale every 2 minutes.

Conversely, a 480-ton throughput cannot be achieved with a single, 0.25-cubic yard compaction chamber press. This throughput would require two presses of that size, and both presses would have to operate continuously at maximum speed.

The matrix appears to be a versatile tool for identifying the bale size or production rate alternatives in terms of an equal over-all performance. In turn, these alternatives suggest tradeoff opportunities between the bale size and the rate of bale production, and the way these two factors may be balanced against each other if additional press design considerations are taken into account.

2. The Effects of Pressure Hold Time on Production

The production effects of variations in the pressure hold time from 15 to 60 seconds are illustrated in Figure 28. The pressure hold times indicated do not, of course, include the time



*Examples referred to in text.

FIGURE 27
The Interrelationship of Waste Compaction Tonnage and
Compaction Rate for Various Bale Weights at Approximately
1 Ton per Cubic Yard Density

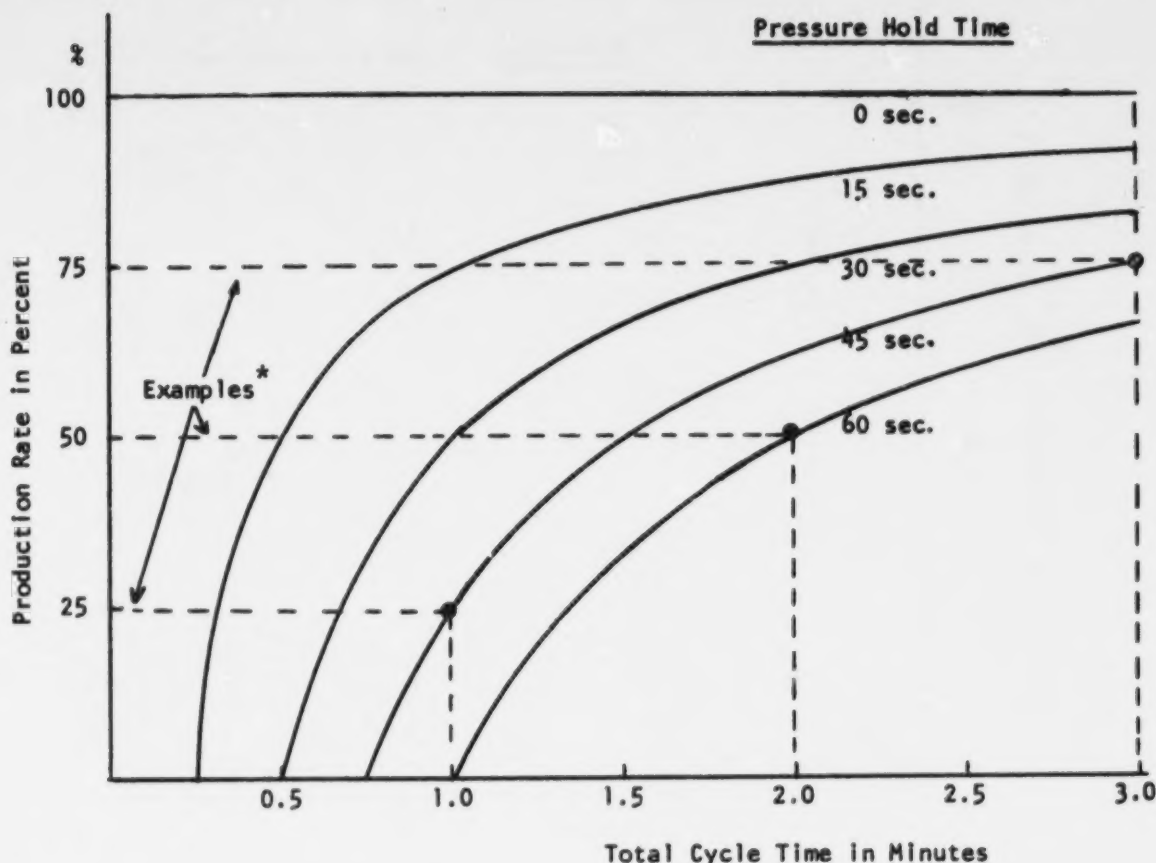
normally required for stroke reversal.

The data represented in Figure 28 are based on the assumption that at the maximum speed attainable the press operates without any pressure hold. Consequently the figure indicates, for example, that in a 1-minute compression cycle a 45-second pressure hold time decreases the production rate from 100 to 25 percent. The same hold time decreases the production rate to 75 percent of the total in a 3-minute cycle. A 60-second pressure hold decreases the production rate to 50 percent of the total in a 2-minute cycle.

It should be mentioned that a maximum

compaction rate of 2.0 bales per minute is assumed to be possible without any pressure hold. At a 0.5-minute or 30-second total cycle time, the stroking rates might become excessively high if, for example, a pressure hold of 15 seconds had to be provided.

The effects of pressure hold time on production (Fig. 28) have to be applied to the matrix shown in Figure 27 to interrelate a pressure hold with specific bale sizes, throughput tonnages, and the corresponding number of bales made per minute. As a result, it can be seen that a decrease in the over-all output due to hold time can be offset by either an increase in the bale size or a speedup, within limits, of



*Examples referred to in the text.

FIGURE 28
The Influence of Pressure Hold Time On
the Production Rate

the production rate, i.e., the number of bales made per minute, or a combination of both. For example, a decrease in the production rate by 50 percent can be offset by an increase of 50 percent in the bale size.

3. Options Concerning Bale Size and Compaction Rates in Terms of Varying Production Requirements per 8-Hour Shift

Table 50 on the following page presents a matrix for the selection of bale size in the compaction chamber and the corresponding compaction rates for throughput requirements ranging from 50 to 500 tons per 8-hour shift.

The compaction rates are expressed in terms of the active or direct cycling operation time required and are stated as rate per minute. The active or direct cycling rate per minute gives the time span within

which the press would have to perform all major compaction movements or steps. Accordingly, this rate determines the speeds at which all the major individual compaction functions would have to be performed. Examples of such functions include: the loading and the closing of the charging box, the movement of the rams in multi-axis compaction devices excluding the pressure hold, the ejection of the bale, and the return of all elements to their zero position.

The active cycling rates given in Table 50 are adjusted to show the effect of hold time varying from 0 to 60 seconds. The addition of a pressure hold time decreases, of course, the time available for the active cycling operations, if the over-all production requirement is kept constant.

TABLE 50
Matrix of Press Capacity Alternatives Based on an Effective Production Time of 480 Minutes Per 8-Hour Shift and on Variations in Overall Throughput, Size and Weight of Bale and Pressure Holding Time

Throughput Requirement Per 8-Hour Shift	Bale Volume ^a or Weight (cu. yd./tons)	Number of Bales Per Shift	Active Cycling Operation Time**									
			0 sec. hold	15 sec. hold	30 sec. hold	45 sec. hold	60 sec. hold					
			(rate per minute and minutes per bale)									
50	0.25	200	0.42	2.40	0.46	2.15	0.53	1.00	0.61	1.65	0.71	1.40
	0.50	100	0.21	(1) 4.80	0.22	(1) 4.55	0.23	(1) 4.30	0.25	(1) 4.05	0.26	(1) 3.80
	0.75	67	(1)		(1)		(1)		(1)		(1)	
	1.00	50	(1)		(1)		(1)		(1)		(1)	
100	0.25	400	0.83	1.20	1.05	0.95	1.43	0.70	2.22	0.45	5.00	(2) 0.20
	0.50	200	0.42	2.40	0.46	2.15	0.53	1.00	0.61	1.65	0.71	1.40
	0.75	134	0.27	(1) 3.58	0.30	(1) 3.33	0.32	(1) 3.08	0.35	2.83	0.39	2.58
	1.00	100	(1)		(1)		(1)		(1)	4.05	(1)	3.80
250	0.25	1000	2.08	(2) 0.48	4.35	(2) 0.23	(3)		(3)		(3)	
	0.50	500	1.04	0.96	1.41	0.71	2.17	(2) 0.46	(2)		(3)	
	0.75	334	0.70	1.43	0.84	1.19	1.07	0.94	1.45	0.69	2.29	(2) 0.44
	1.00	250	0.52	1.92	0.60	1.67	0.70	1.42	0.85	1.17	1.09	0.92
500	0.25	2000	(2)		(3)		(3)		(3)		(3)	
	0.50	1000	2.08	(2) 0.48	(2)		(3)		(3)		(3)	
	0.75	667	1.39	0.72	2.13	(2) 0.47	(2)		(3)		(3)	
	1.00	500	1.04	0.96	1.41	0.71	2.17	(2) 0.46	(2)		(3)	

* Density in the compaction chamber set at one ton of material per one cubic yard

•• All data are slightly rounded and expressed in the decimal system

(1) Rates are lower than guideline of 0.33 active cycles per minute

(2) Rates are higher than guideline of 2.0 active cycles per minute

(3) Cannot be achieved

The figures in *italics* give the minutes allowed for the active cycling operations in the production per bale, but do not include a holding time.

The total amount of time available for the production per bale, i.e., for the total cycle including any hold time, is given in Table 50 in the fourth column headed "@0 sec. hold." The data are expressed in the decimal system. Thus, a value of 2.4 minutes is the equivalent of 144 seconds or 2 minutes and 24 seconds.

The time span in Column 4 is determined by dividing the total production time by the number of bales to be produced per shift. This span represents the total cycling time available. It does not change regardless of the relationship that might be found between the portions of active cycling time and hold time, provided a pressure hold is applied. If no such hold is applied, the total cycling time is equal to the active cycling operations time.

In evaluating the data given in Table 50, it should be recognized that they are calculated on the basis of an effective working time of 480 minutes per 8-hour shift. This base was chosen to show the maximum production achievable.

The data underlined in the table indicate the interrelationships which fall within the limits of the guidelines established for this study. They show, for example, when and under what specific operating conditions it is possible to accommodate a given amount of pressure hold time. They also show the variations possible in the corresponding sizes of the bale in the compaction chamber as well as the corresponding number of bales which must be produced under the conditions given. Conversely, the data not underlined represent operating speeds which allow either less than 30 seconds or more than 3 minutes for the accomplishment of all the required major compaction movements or steps.

To facilitate a realistic selection of press capacity for rail-haul and other applications, it is necessary to adjust the nominal press capacity downward to more practical production levels. Within the scope of this project, it was decided to follow the guidelines outlined in Chapter II of this report. It might be remembered that those guidelines suggest an effective working time of 360 minutes per 8-hour shift. Thus the actual rate of production is pegged at 75 percent of the nominal press capacity.

Table 51 on the following page presents a matrix similar to the one shown in Table 50 but based on an effective working time of only 360 minutes per 8-hour shift. Combined, the data in both tables indicate that a substantial degree of operational flexibility is provided for the actual day-to-day execution of the compaction process. This holds true specifically if the presses are designed to serve the

100 and 250 tons per 8-hour shift production requirements. Considering the value of pressure hold time for the compaction of wet and/or dry and difficult-to-compact materials, this flexibility may be needed to assure successful year-round compaction operations.

Furthermore, the data presented in both tables indicate that a wide choice is given for the selection of tradeoffs. In particular, significant tradeoffs appear to be available with respect to the size of the compaction chamber and the use of pressure hold time.

A 100-ton per 360 minutes process throughput requirement, for example, could be achieved satisfactorily with bale sizes ranging in the compaction chamber from 0.25 to 0.75 cubic yard. Furthermore, a press compaction chamber for a bale of 0.50 or 0.75 cubic yard could, under the same throughput condition, accommodate a holding time up to 1 minute. Such a hold time, as reported in Chapter III, could substitute for about 500 to 750 psi of applied pressure and reduce, in turn, the press construction requirements resulting from the specifications of a given face or applied pressure. As will be shown, both the size of the compaction chamber and the amount of face pressure required are in addition to the speed of operations, major factors in shaping the cost of high-pressure compaction.

Over-all, the data indicate that series of alternate performance specifications appear suitable for operations within the guidelines and constraints given. However, since each individual specification carries different implications for both the process cost and operations, it is necessary to tailor the requirements to the local needs. Thus, individual press performance specifications must be based on local operating conditions as well as the characteristics of the materials to be compacted and the influence of the wet and dry days encountered.

4. Press Capacity in Terms of Transfer Stations for the Rail-Haul of Solid Wastes

Disregarding special local conditions, the above information can be used to indicate in broad terms some of the basic configurations for using high pressure compaction of solid wastes in selected rail-haul transfer stations. These basic configurations are based purely on one-shift operations which furthermore are pegged at only a 75 percent level of efficiency.

a) 50 tons per 8-hour shift capacity

Without necessitating high compaction rates, the 50-ton station can be served by one press having a bale volume of 0.25 cubic yard in the compaction

TABLE 51
Matrix of Press Capacity Alternatives Based on an Effective Production
Time of 360 Minutes Per 8-Hour Shift and on Variations in Overall Throughput,
Size and Weight of Bale and Pressure Holding Time.

Throughput Requirement Per 8-Hour Shift	Bale Volume* or Weight (cu.yd./tons)	Number of Bales Per Shift	Active Cycling Operations Time**									
			@ 0 sec. hold	@ 15 sec. hold	@ 30 sec. hold	@ 45 sec. hold	@ 60 sec. hold					
			(rate per minute and minutes per bale)									
50	0.25	200	0.55	1.80	0.64	1.55	0.77	1.30	0.95	1.05	1.25	0.80
	0.50	100	0.28 (1)	3.60	0.30 (1)	3.35	0.32 (1)	3.10	0.35	2.85	0.38	2.60
	0.75	67	(1)		(1)		(1)		0.21 (1)	4.62	0.23 (1)	4.37
	1.00	50	(1)		(1)				(1)		(1)	
100	0.25	400	1.11	0.90	1.54	0.65	2.50 (2)	0.40	6.67 (2)	0.15	(3)	
	0.50	200	0.55	1.80	0.64	1.55	0.77	1.30	0.95	1.05	1.25	0.80
	0.75	134	0.37	2.69	0.41	2.43	0.46	2.19	0.51	1.94	0.59	1.69
	1.00	100	0.28 (1)	3.60	0.30 (1)	3.35	0.32 (1)	3.10	0.35	2.85	0.38	2.60
250	0.25	1000	2.78 (2)	0.36	(2)		(3)		(3)		(3)	
	0.50	500	1.39	0.72	2.12 (2)	0.47	(2)		(3)		(3)	
	0.75	334	0.92	1.08	1.20	0.83	1.72	0.58	3.03 (2)	0.33	(2)	
	1.00	250	0.69	1.44	0.84	1.19	1.06	0.94	1.45	0.69	2.27 (2)	0.44
500	0.25	2000	(2)		(3)		(3)		(3)		(3)	
	0.50	1000	2.78 (2)	0.36	(2)		(3)		(3)		(3)	
	0.75	667	1.85	0.54	3.45 (2)	0.29	(2)		(3)		(3)	
	1.00	500	1.39	0.72	2.13 (2)	0.47	(2)		(3)		(3)	

* Density in the compaction chamber set at one ton of material per one cubic yard

** All data are slightly rounded and expressed in the decimal system

(1) Rates are lower than guideline of 0.33 active cycles per minute

(2) Rates are higher than guideline of 2.0 active cycles per minute

(3) Cannot be achieved

The figures in *italics* give the minutes allowed for the active cycling operations in the production per bale, but do not include a holding time.

chamber.

Furthermore, a pressure hold time ranging from 0 to 60 seconds could be accommodated without difficulty.

A 0.50-cubic yard bale size compaction chamber press might be suggested for this capacity transfer station if pressure holds of 45 or 60 seconds were to be applied.

b) 100 tons per 8-hour capacity

A 100-ton station appears to be especially well served by presses with bale sizes of 0.50 or 0.75 cubic yard in the compaction chamber. In both cases a pressure holding time from 0 to 60 seconds could be provided.

The use of a 0.25-cubic yard compaction chamber bale would require relatively high speed press operations and be limited to not more than a 15-second pressure hold.

In contrast, a 1 cubic yard bale-compaction chamber press could be used for relatively slow operations. However, the selection of such a press only appears to be reasonable in terms of the data presented if a pressure hold of 45 or 60 seconds is contemplated.

c) 250 tons per 8-hour capacity

A 250-ton station requires that the volume of the bale in the compaction chamber be not less than 0.50 cubic yard.

If pressure hold times of 15 or 30 seconds are desired, then the compaction chamber bale volume would have to be 0.75 cubic yard.

A pressure hold time of 45 seconds requires that the bale have volume of 1.0 cubic yard in the compaction chamber.

A pressure hold time of 60 seconds cannot be accommodated within the operational constraints given for the analyses of this study.

d) 500 tons per 8-hour shift capacity

A 500-ton station can be served only by presses operating at the comparatively high speeds of 0.54 or 0.72 minute per total cycle. At this speed the production rates would be equivalent to an output of one to two bales per minute. The corresponding bale volume in the compaction chamber would have to be 0.75 or 1.0 cubic yard, respectively.

If any pressure hold-time were to be applied, a 500-ton station would have to be served by multiple compaction units. For example, two presses as indicated for the 250-ton transfer station throughput requirements, or five units as indicated for the 100-ton process throughput, could substitute for a single 500-ton per 8-hour shift press.

The 500-ton compactor represents the largest

single unit possible on the basis of the bale sizes and compaction rates called for in the guidelines.

5. Conclusions

In terms of the total set of transfer stations investigated for the rail-haul of solid wastes, the 100- and 250-ton presses appear to provide a maximum of operational flexibility if a nominal 8-hour throughput is to be processed within 6 hours.

Thus, since the number of potential applications is quite large in the 100- to 250-ton 8-hour shift size range, it appears that prime emphasis should be given the development of presses with a 0.50- and/or 0.75-cubic yard bale size in the compaction chamber.

Selection of this size press implies that very high volume transfer stations would be served by more than a single compaction unit. It is not necessary in such cases to plan for any backup or standby units since the basic operations are based on just one 8-hour shift per day and, in addition, at an efficiency level of only 75 percent of the rated capacity. Any equipment breakdown or operational delays could therefore be handled easily by a temporary speedup of the operations, overtime schedules or, at worst by a second shift.

III. HYDRAULIC PRESSURE CONSIDERATIONS

In order to gauge the effects of variations in the face pressure applied, it is necessary to investigate some factors which are important in the utilization of hydraulic pressures. The factors considered here concern (a) the availability of hydraulic components, (b) the consequences of unit pressure variations with respect to the size of the hydraulic rams and cylinders, and (c) the use of hydraulic forces in the compaction of solid wastes.

It should be emphasized that this section of the investigation is based on the assumption that the first solid waste presses would operate primarily by hydraulic means of pressure generation and transmission. This assumption appears to be justified by the process implications resulting (as outlined in Chapters II and III) from the compaction behavior of the solid waste input materials usually encountered in municipal refuse collection.

1. The Availability of Hydraulic Components and Parts

A brief survey of the utilization of hydraulic components, including pumps, pipes, valves, accumulators, and fittings, indicates that most heavy press manufacturers design their equipment to operate at hydraulic pressures of 3,000 to 3,500 psi. According to the "Fluid Power Handbook and Directory," compiled by the editors of "Hydraulics

and Pneumatics" magazine, this range of pressures apparently represents the highest level of pressures for which the necessary components are considered more or less staple items and are most widely available.

Of course, hydraulic components are made for operations requiring higher hydraulic pressures. Specifically, there appears to be a trend toward use of 5,000 psi hydraulic pressure systems. Hydraulic systems operating at even higher pressures are in existence but are not recommended for the normal production line operations requiring both heavy duty service and a high level of reliability.

In accordance with these findings, it was decided to base the explorative investigations on utilization of hydraulic pressure systems operating at 5,000 psi or less.

2. The Relationship Between the Diameter of the Hydraulic Cylinder and Variations in the Pressure Applied

To keep the following investigations within manageable proportions, it was decided to base all calculations on the two bale/compaction chamber sizes identified above—0.50 and 0.75 cubic yard.

Bale volumes of 0.50 and 0.75 cubic yard in the compaction chamber are equivalent to roughly 13 and 20 cubic feet respectively. If the bale were to be a cube, these volumes, in turn, would identify the lengths of the sides as 2.35 or 2.71 feet respectively. As a result, the relevant compaction pressures would have to be applied to an area of 5.52 or 7.34 square feet.

Four levels of hydraulic pressures and three levels of applied pressures were considered. The hydraulic pressures ranged from 1,000 to 5,000 psi and the applied pressures from 1,000 to 3,000 psi.

The interrelationship between hydraulic cylinder or ram area, hydraulic pressure, and pressure applied is, in terms of the above sets of values, graphically presented in Figure 29 on the following page. The area of the hydraulic ram is given by the relationship

$$A_h = \frac{A_c P_c}{P_h}$$

where A_h is the hydraulic ram area, A_c the compaction area, P_c the compaction pressure and P_h the hydraulic ram pressure.

The data do not reflect the effects of pressure hold time. An example of the pressure hold effect on the ram diameter is shown for the 0.75-cubic yard compaction chamber bale and a hydraulic pressure level of 3,000 psi. It might be remembered that a pressure hold may be used as a substitute for 500 to

750 psi in applied pressure.

The curves suggest that diameters of the hydraulic cylinders might need to be very large, depending on (a) the amounts of hydraulic and applied pressures used and (b) their pressure correlations. This finding is predicated on the assumption that a single cylinder delivers the total pressure applied through the pressure face.

However, within the constraints given, the curves also can be used to identify tradeoffs in terms of the cylinder diameter requirements at the hydraulic base pressures given. To reduce the hydraulic cylinder diameter, for example, an applied pressure of 2,000 psi can be achieved with two cylinders, each smaller in diameter and each delivering the force of 1,000 psi in applied pressure. Correspondingly, a single ram delivering 3,000 psi of applied pressure can be replaced by two or three rams totaling that pressure.

Also, the applied pressures can be generated by one or more hydraulic pressure systems. For example, 3,000 psi of applied pressure can be provided by three rams each giving 1,000 psi from one 5,000 psi hydraulic system — or by two rams, one operating with 5,000 psi of hydraulic pressure, the other with 3,000 psi.

In conclusion, the data in Figure 29 indicate that a wide choice is available to press designers for the execution of equipment performance specifications. Since hydraulic cylinders of less than 30 inches in diameter are commonly preferred for 3,000-psi hydraulic systems, the data suggest a specification of 2,000 psi in applied pressure, some holding time, and a bale volume not exceeding 0.75 cubic yard in the compaction chamber.

Thus, the hydraulics information tends to support the selection of presses made previously on the basis of press capacity. Requests for bids on hydraulic equipment in these general pressure ranges should elicit a widespread response.

3. The Utilization of Hydraulic Forces in the Compaction of Solid Wastes

The compaction curves in Chapter III of this report indicate that initially a relatively small amount of pressure is needed to achieve a significant volume reduction of solid waste materials. About 80 percent of the total volume reduction is achieved by about 1,000 psi which is half the total pressure applied at a maximum face pressure of 2,000 psi. Similarly, 1,000 psi amounts to only one-third the ultimate pressure applied if the maximum face pressure is 3,000 psi.

The approximate relationship is described again in Figure 30, showing volume reduction and

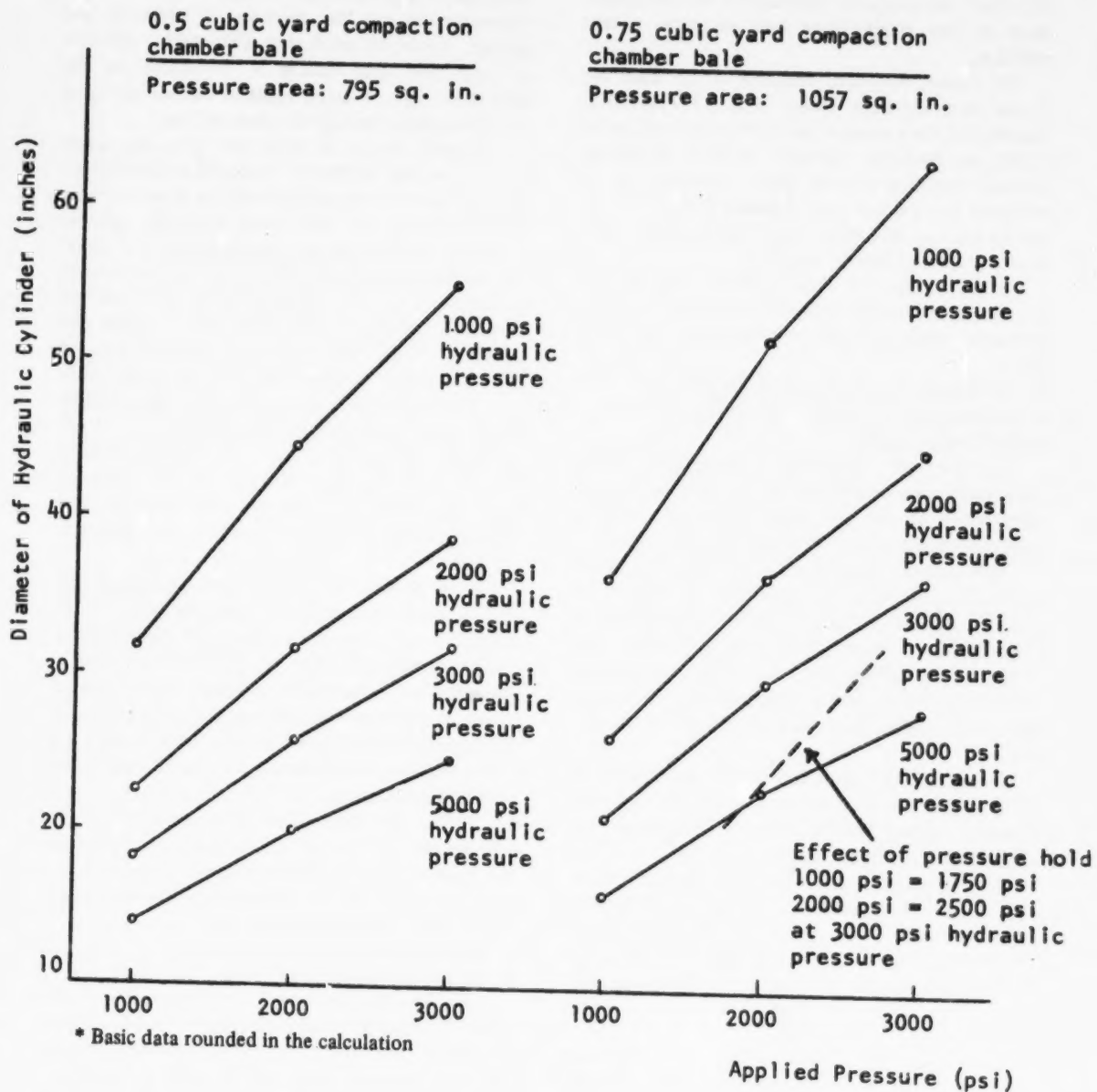


FIGURE 29
Interrelationship Between Diameter of Hydraulic Cylinder,
Hydraulic Pressure, and Pressure Applied for Two Sizes of
Bales in the Compaction Chamber*

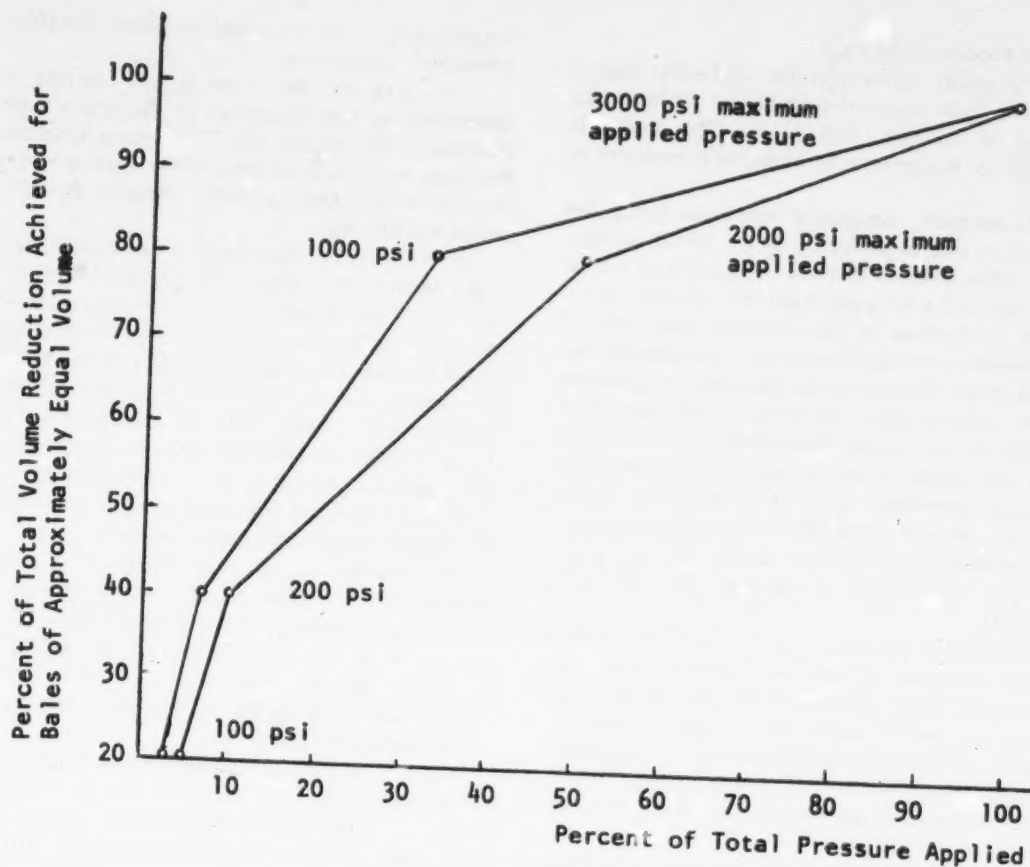


FIGURE 30
Approximate Relationship Between Volume Reduction and Pressure
Applied for Maximum 2,000 and 3,000 psi Applied Pressure Systems

maximum pressure application at face pressures of 2,000 and 3,000 psi in percentages.

The curves in the above figure show that the top portion of the applied pressure, and consequently the full application of the hydraulic forces, are needed for only a minor portion of the total volume reduction process. To achieve a harmony between the total pressure generating capacity and cost-benefit ratios to volume reduction, the curve indicates that pressures in the lower range should be specified as long as they are suitable for the bale production requirements covered in this report. The curves also might suggest that a single-stage compaction process, because of the findings on volume reduction patterns, might be less advantageous than a two- or three-axis compaction system.

Evaluation of Figure 30 should recognize that for

the rail-haul of solid wastes the choice of the applied pressures is based not only on the achievable volume reduction but also on the highly important requirement of bale stability.

A large amount of applied pressure is needed to provide this stability regardless of the low relative value of the high pressure in volume reduction.

IV. PRESS DESIGN CONSIDERATIONS CONCERNING PRESS LOADING, THE CHARGING BOX, AND THE GEOMETRIC SHAPE OF THE COMPACTION CHAMBER

The press loading, the size of the charging box and the geometric shape of the compaction chamber have a direct bearing on the operational requirements as well as the implementation of the performance specifications of the press design.

1. The Loading of the Press

The results of the previous discussions suggest that solid waste compaction equipment might have to operate at relatively high speeds. This makes it essential for the press to be loaded in a minimum of time.

Furthermore, compaction tests made during this project, as well as previously by the APWA rail-haul study team, indicate that the compaction of sets of precompacted solid waste bales into one bale causes severe laminations in the ultimate bale, even if performed at very high pressures. Poor adhesion was found at the interface of the precompacted portions of the ultimate bale even when a final pressure of 18,000 psi was applied. In contrast, the compaction of a full charge of wastes, not precompacted with pressures exceeding those of a compactor truck, produces no such lamination effects. Consequently, the press loading facilities should be capable of handling a full charge of uncompacted solid waste materials.

In view of the nature and composition of solid waste mixtures, it becomes apparent that any forced-feed filling system may be highly complex and costly. As noted earlier, such a system must be capable of handling simultaneously an extremely large variety of wet and dry materials ranging in size from refrigerators and bedsprings down to tissue papers and food scraps.

Thus, to provide for a fast and easy feed of the input materials, the press should be designed for a top or gravity-fill batch method of loading. Since implementation of the press loading system is considered part of the transfer station development, it is discussed in the APWA rail-haul study.

2. The Charging Box

In terms of performance and design specifications, it is necessary to determine the dimensions of the charging box volumetric requirements and the size of the opening. This finding is based on the assumption that total volume reduction is to be achieved by the press alone.

The data in Chapters II and III of this report indicate that for handling of most normally delivered residential wastes, the press would have to provide a volume reduction ratio of 15:1. For a 0.50- or 0.75-cubic yard bale in the compaction chamber press, this necessitates a charging box capacity of 7.5 or 11.25 cubic yards, respectively.

In a gravity-fill batch loading system, however, an even filling of the charging box is not easily guaranteed. Furthermore, oversized wastes such as sofas or bedsprings might require an even larger

charging box; the above volume represents, therefore, a minimum requirement.

The size of the charging box opening is determined by the dimensions of the largest items included in the material mix. Thus, in an ideal case the cross sectional dimensions of the opening would have to be sufficient to handle refrigerators, sofas, tables, and freezers.

As a result, the dimensions of the charging box might have to be increased by perhaps 50 percent over the volumetric values given above. For example, the side lengths of an 11.0-cubic yard charging box would be only 2.2 yards, or 6.6 feet, if the box is cube-shaped. This, in turn, would represent a pressure face area of 43.5 square feet or 6,264 square inches. For a 7.5-cubic yard charging box, the corresponding side length dimensions would be approximately 1.9 yards or 5.7 feet, and the pressure face area would be 32.5 square feet or 4,680 square inches.

An increase of the side lengths of a cubic charging box to about 10 feet would produce a volume approximating 37 cubic yards. This would correspond to a pressure face area of 100 square feet or 14,400 square inches. If, in turn, 100 psi of pressure were to be applied to this area, a total force of 720 tons would be required.

In reviewing all the arguments presented thus far, it becomes obvious that the application of a 720-ton force to a 10 by 10-foot pressure face is technically conceivable. However, an application of 2,000 psi, or 1 ton per square inch, appears to be needed for the production of solid-waste rail-haul bales and would require a force of 14,400 tons on the ram. Although presses with such force applications are made, they unfortunately are of relatively exotic design.

Thus, the implications of the charging box data suggest development of a multi-stage compaction press. Furthermore, attention must be given to the data which indicate the presence of many voids in the incoming refuse densities, and therefore, the small forces needed for initial volume reduction. It appears advantageous to give the cover of the charging box an active function in the volume reduction process. This, by itself, presupposes the use of at least a two-stage compression system.

For example, the application of 10 psi over a 10 by 10-foot area would require a total force of 72 tons. Considering point loading, such a force is more than adequate to crush oversized solid waste items sufficiently to fit into a smaller charging box. Even a force of only one-fifth that size, or 14.4 tons, and representing a pressure of 2 psi over the area, might be all that is required. In view of the size of the total

area, a significant portion of such a cover force could be supplied by the weight of the cover itself.

Consequently, an active use of the charging box cover in the compaction process can reduce the pressure face area to which the second stage compaction forces are applied. In addition, a combination of the cover function with a compaction function should be considered, since it would reduce or eliminate a time element and therefore a cost element that otherwise would have to be incorporated in the over-all compaction operations.

In conclusion, the charging box analyses indicate that the selection of a 0.50- or 0.75-cubic yard bale in the compaction chamber press is reasonable for the box dimensions required. With an inclusion of oversized items in the solid waste mix, the charging box dimensions appear to require the selection of these bale-size specifications.

3. The Geometric Shape of the Compaction Chamber

For purposes of this project, the geometric shape of the compaction chamber is derived from the specifications for the bale form as outlined in Chapter II. However, for non-rail-haul applications, other shapes might prove desirable. Thus, to indicate other applications of the project findings, it was found necessary to consider other than rectangular shapes for the compaction chamber.

In terms of press design, many geometrical shapes of the compaction chamber are theoretically possible, including cube, rectangular prism, hexagonal prism, and cylindrical shape or ball. Some of these configurations, such as a cube or a cylindrical shape, lend themselves to a multi-stage compaction approach. Others, such as a ball, might require the compaction to be accomplished by a single stroke.

However, in considering various geometric shapes of the bale and the compaction chamber, it is important to take into account the nature of the materials to be compacted. Certain geometrical shapes such as a ball are impossible to make if the input materials cannot be pre-processed to provide sufficiently constant behavior patterns for the materials under compaction. Consequently, certain geometric shapes of compacted materials are possible only in cases where the input materials are homogeneous, as, for example, in the manufacture of pills in the pharmaceutical industry. Thus, a compaction of heterogeneous solid waste mixtures into shapes such as a ball or a hexagonal prism should not be attempted unless an adequate pre-treatment of the materials is assured.

A brief survey of the applicable studies tends to confirm this finding. It indicates that for the compaction of heterogeneous materials such as metal scrap or mixed papers, only cubical or rectangular

bale configurations are referenced. No other geometric shapes appear to have been suggested for use in standard practice.

In the light of these findings plus the test results reported in Chapter III and the conclusions drawn in Chapter II, it was decided to confine the press specifications to the production of square or rectangular bales. Accordingly, the following analyses of the compactor frame are based exclusively on these shapes.

V. PRESS DESIGN CONSIDERATIONS CONCERNING THE PRESS FRAME

The frame represents a large portion of the total weight and cost of a compaction press. For metal scrap balers operating at about 2,000 to 2,500 psi of applied pressure, the frame often is estimated to account for 40 to 45 percent of the total weight and/or cost of the unit. Thus, since solid waste disposal is highly sensitive to cost, it becomes important to investigate some of the guidelines governing the design of press frames.

1. The Press Frame in Terms of Solid Waste Compaction

The frames used by relatively heavy presses generally serve two basic functions. First, they carry and/or contain, as a rule, the reaction forces resulting from the application of pressure and/or impact. Secondly, they provide, to varying degrees, dimensional control for the compaction or fabricating operations performed.

The second function, in particular, causes a considerable over-design of the frame as compared to the requirements for the first function. Specifically, the frame in these cases frequently is designed on the basis of stringent rigidity needs. These, in turn, compel the main structural-frame members to operate at a low percentage of their actual strength in order to eliminate the deflections and elongations which cannot be tolerated. As a result, press frames are very heavy and have a high weight-to-force ratio for the pressures actually applied in the compaction process.

In contrast, the dimensional variations of concern for many fabrication and compaction processes are not critical in the high pressure compaction of solid wastes. Here some variation of the bale volume will have to be accommodated in the compaction chamber because of unavoidable variations in the solid waste composition. Furthermore, the amount of springback per individual bale after compaction is both variable and substantial even at identical compaction chamber dimensions.

Stringent dimensional control of the bale thus is not possible, nor is it required for solid-waste rail-haul. The ratio of frame weight to the amount of

compaction pressure applied does not have to be as high as that normally found in compaction equipment.

Solid waste compaction by hydraulic means involves a relatively slow and gradual application of the compression load without significant or continuous impact loadings. In turn, the absence of dynamic loading in the form of impact can be taken as added justification for development of lighter-than-usual press frames.

Point loading can occur during the compaction of solid waste mixtures. Although it is not likely to cause damage to a lightweight frame suitable for the pressures involved, the possibility of significant point loading does exist. It appears that this fact, shown in Figure 22, Chapter III, should be considered in the design of a press and might deter the use of an absolute minimum-weight press frame for solid-waste compaction units.

Over-all, the above considerations encourage an investigation of press frame design alternatives aimed at construction of lighter frames than those found in most existing compaction equipment. But while this suggestion presupposes future improvements existing frames are without doubt, technically suitable for the construction of solid-waste presses.

2. Basic Considerations for a Minimum-Weight Frame

The application potential of minimum-weight frames to solid-waste presses merits further investigation here, because of the importance of cost reduction in solid waste disposal and the promise of solid-waste high-pressure compaction. In principle, all the above arguments suggest that the design criteria for a minimum-weight, solid-waste press frame might be confined to the containment of the pressure reaction forces excluding impact loading.

Within this context, it is essential to make the total system reliable in terms of structural fatigue and component wear. This requires that the frame members be uniformly stressed in tension, preferably by pre-stressing or, if necessary, by the compaction process itself. For example, a frame design concept could be used which would resemble a pre-tensioned wire rope system.

It is recognized, of course, that the frame for solid-waste presses might not have to meet the sophistication normally associated with such a system. For example, welded plate or steel strapping might be used as frame members to reduce structural costs. Other alternatives, reminiscent of aerospace minimum-weight - maximum-strength designs, might be substituted for the massive side frame forgings and tie rods commonly used.

The specific implications and execution of the press frame design concepts touched on above are not entirely new. Presses utilizing the underlying design principles have been built in Europe. Furthermore, the IIT Research Institute in Chicago uses a lightweight frame made from steel strappings for the end load restraint of a high-pressure chamber.

Thus, a distinct possibility exists for applying minimum-weight press frame concepts in the design of solid-waste high-pressure compactors. These concepts may result in equipment of lower cost and thereby increase the application potential of this solid waste disposal process. They further justify the continuation of the investigation of lightweight frames.

3. Description of an Existing Single-Axis Lightweight Press Frame

As mentioned, IIT Research Institute has developed, constructed and used successfully a lightweight frame for a high-pressure chamber end load restraint. It appears that an adaptation of the IITRI concept could, for example, be used quite effectively for solid waste compaction presses. However, IITRI's banded frame concept is not singled out as the only realistic possibility for a lightweight, low cost frame design. Rather, the IITRI approach has been chosen as an example because it represents the best documented system available within the scope of this study.

Over-all, the IITRI strap-frame is capable of carrying 9,000 psi of face or applied pressure for its 84-x-48-inch end section. This is equivalent to a force of more than 18,000 tons on the ram. The face pressure is at least four times as great as the face pressures currently contemplated for the compaction of solid-wastes.

The geometry of the IITRI press frame is illustrated in Figure 31. It indicates the location of the side and end frames and the direction of pressure application. Specifically, it identifies the factors which influence as discussed below the frame weight, i.e., frame length, frame width, frame depth and the loading applied.

In the IITRI press, the side or primary frame members obey the criterion of minimum weight in being required to carry only tensile stresses. Furthermore, the side and end frame materials were selected from the standpoint of minimum cost, including both the material and fabrication expenditures.

To satisfy the criteria of minimum weight and cost for the primary frame, IITRI chose a 1022 steel strapping with a cross section of 4.0 x 0.072 inches. Thus, the frame is constructed of stacks of layered

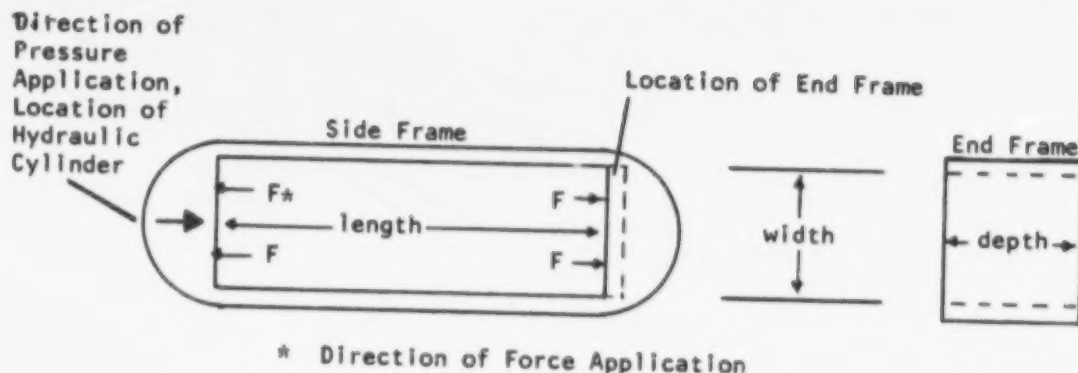


FIGURE 31
Concept of the Geometry of the IITRI Lightweight Press Frame

strapping to reach the total end load requirement of approximately 36.3 million pounds or 18,150 tons. Over-all, the IITRI frame is designed to operate for more than one million cycles at a tension stress of 35,000 psi.

It is important to recognize that a lightweight frame within the context of this discussion is composed of two distinct elements:

- a) a high-tensile stress restraining system, and
- b) a bearing plate system or end frame progressively stressed by the increase in the compaction pressures applied.

The end frame, according to IITRI, can be designed to accommodate varying loads over the face of the end plate. It could be made from one solid plate, or from stacked solid plates which have the advantage of low mill and fabrication cost. Point loading might occur in the compaction of residential and commercial solid wastes or their equivalents. However, the compressive stresses in the end plates are estimated in the order of magnitude of the compaction pressures, provided the applied pressure exceeds 2,000 psi.

4. Application of the Lightweight Frame Concept to Multiple-Axis Compacting

The lightweight press frame concept appears to lend itself to a multiple-axis compaction of solid waste materials.

In solid waste compaction, a single-axis compactor must have a very long tensile frame, designed for the maximum compaction pressure, because of the high volume reduction ratios. A

double-axis compactor, in contrast, requires a shorter—perhaps very much shorter—tensile frame for the containment of the peak compaction forces. In double-axis compaction, the volume reduction is accomplished by two rams, and it is commonly the shorter of the two rams that applies the higher compaction forces. Hence, compared to single-axis compaction, the tensile or primary frames usually will be lighter in double-axis compaction systems.

In principle, and with only a few exceptions, the weight of the tensile frame decreases as additional compaction stages are added to the system. This results from an improved proportioning of the total loading on the press frame, achieved by tailoring each of the frames to contain only a portion of the total pressures and ram travel distances involved.

However, the actual tradeoff between the addition of compaction stages and a decrease in the weight of the tensile frame is governed, to a large degree, by practical press operating and design considerations. Too many individual frame elements restrict the access to the press and might encumber both the charging of the materials and the removal of the bale. Furthermore, too great a dispersion of the operating elements undoubtedly will complicate the design and construction of the press. It may also increase, perhaps substantially, the total cost of the individual press elements such as the hydraulic piping, cylinders and controls.

In addition, end frames present some unique problems. In contrast to the tensile frame parameters, the end frame requirements and weights always

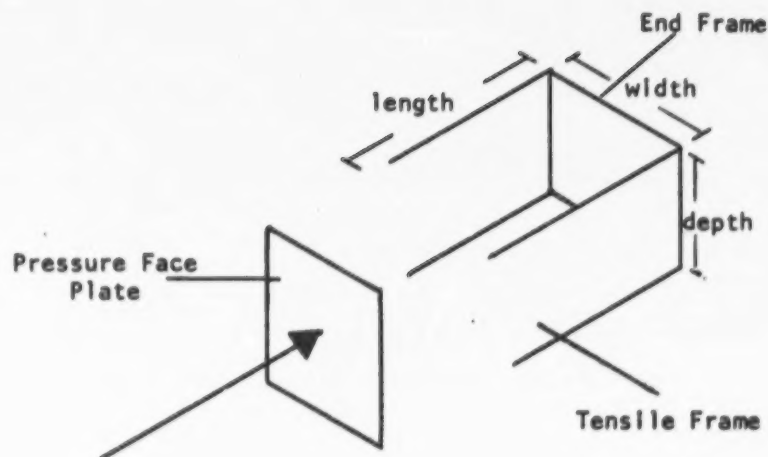


FIGURE 32
Configuration of the Compaction Chamber

increase with the addition of compaction stages. A double-axis compactor, for example, might require two end frames. Both of these may be designed for an equal amount of force, or one may be designed for the peak compaction and the other for the lesser, perhaps, greatly reduced pressure requirements.

Comparing a single-axis to a double-axis compactor and assuming an identical size of the bale, the end frame receiving the maximum forces is, in both cases, capable of withstanding all the pressures as applied through the whole pressure range. But double-axis compression may require a second end frame and therewith additional weight to stop the forces applied in the first compaction stage. Thus, while weight is, in most cases, taken from some portions of the tensile frame by splitting the total compaction process into separate stages, weight appears always to be added by the same approach to the end frame system. The total weight of the end frames is almost always greater in multiple- than in single-axis compaction systems.

In evaluating the application potential of the lightweight frame concept to the design of solid waste compactors, it must be remembered that (a) the volume reduction ratio is substantially higher than that usually found in other pressure application processes, and (b) most of the volume reduction, in terms of the ultimate force, is achieved by the application of comparatively low pressures.

5. Effects of Compaction Chamber Dimensions on the Press Frame

The geometry of the compaction chamber influences the requirements for both the side or tensile frame and the end frame.

The configuration of the compaction chamber, referred to in the following discussions, is identified in Figure 32. It should be emphasized that in these discussions the length of the chamber is always presumed to be parallel to the direction of the final pressure application.

At a given amount of pressure, the end frame requirements are determined only by the width and depth of the compaction chamber. They are not affected by changes in the length of the compaction chamber unless the end frame area changes. For example, at 2,000 psi of applied pressure and the absence of pressure losses in the compaction, a 2-square foot end frame always would have to sustain a 288-ton load, regardless of the length of the compaction chamber.

On the other hand, the requirements for the side or tensile frame are affected by changes in the width and depth, as well as the length of the compaction chamber. Changes in just the length of the compaction chamber affect the design requirements least. They require that the side frame be lengthened or shortened, but they do not demand changes in its capacity for end load restraint as long as the end

frame area is kept constant.

However, changes in length of the compaction chamber become highly significant to the side frame requirements if a constant chamber volume is postulated. In this case, the area of the end frame and the length of the compaction chamber are interdependent. An increase in the length of the compaction chamber will decrease the end frame area and vice versa. In turn, the end-load restraining requirements, and therefore the tensile frame

requirements, may vary considerably.

An example of the interrelationship between variations in the lengths of the compaction chamber and corresponding end-load restraining requirements is illustrated in Figure 33. The interrelationship is shown on the basis of an 8-cubic-foot chamber volume for applied pressures of 1,000, 2,000 and 3,000 psi.

An analysis of the three curves in Figure 33 indicates the same effects, regardless of the

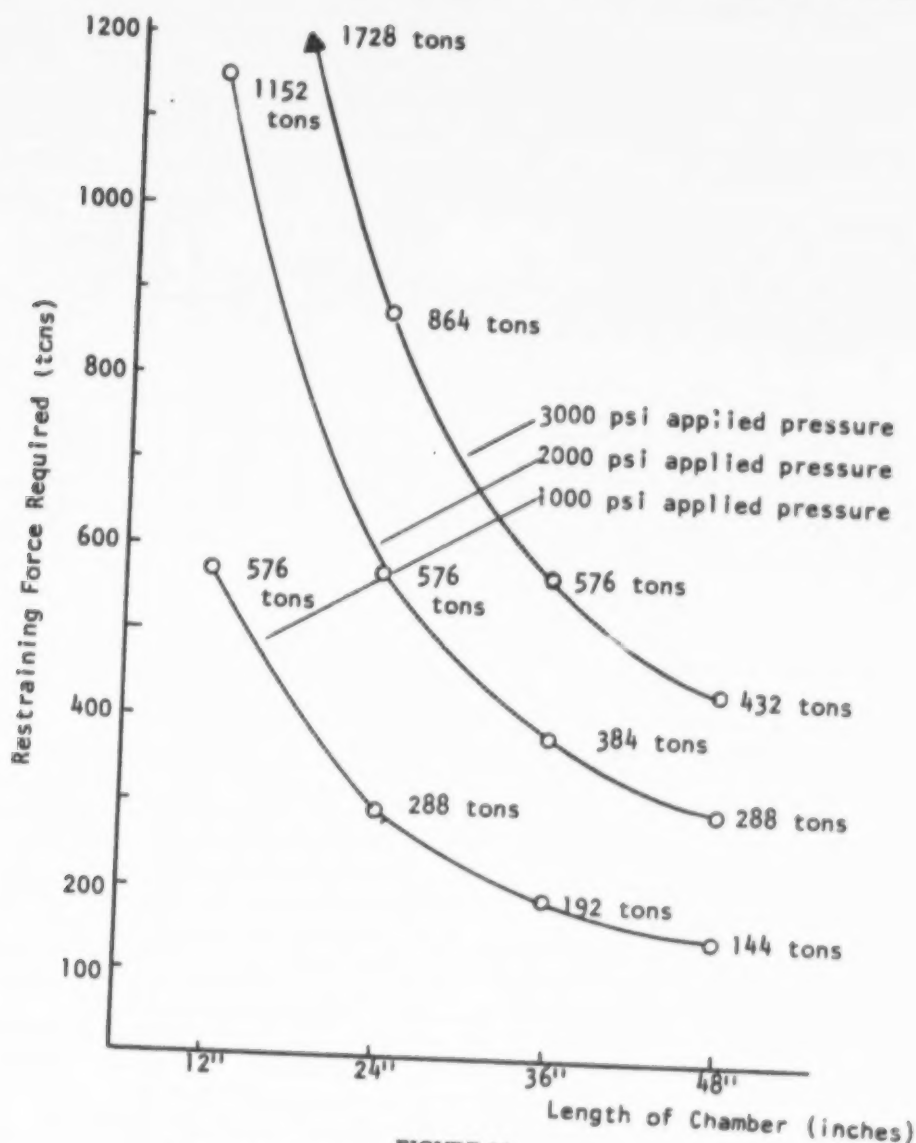


FIGURE 33
Selected Interrelationships Between Length of Compaction Chamber and the End Load Restraining Forces Required for a Chamber Volume of Eight Cubic Feet

magnitude of pressure applied. Within the limits given, a doubling of the length of the compaction chamber reduces the end-load restraining requirements by one-half.

The end frame load-bearing requirements will change correspondingly in the case of a relatively constant compaction chamber volume, which might be required for the rail-haul of solid wastes. This is illustrated in Table 52 for compaction chamber length variations from 12 to 48 inches and a total chamber volume of, again, 8 cubic feet.

corresponding hydraulics involved. The postulate of a stable, cohesive bale requires that sufficient pressure be transmitted throughout the solid waste mixtures and, therefore, to the far end of the compaction chamber.

6. The Operational Life of the Press Frame

The operational life of the press frame is determined primarily by the applied number of cycles of a given pressure or load.

A thorough analysis of this problem, unfortunately, was outside the scope of this project.

TABLE 52
Variations in the Total End Frame Load Bearing Requirements Resulting
from Changes in the Length of the Compaction Chamber at a Load of 2000 psi
Applied to the End Frame and a Constant Chamber Volume

Compaction Chamber Volume (cu. in.)	Compaction Chamber Dimensions			End Frame Dimensions			Load Rqts. at 2000 psi Applied Press. (tons)
	Length (in.)	Width (in.)	Depth (in.)	Width (in.)	Depth (in.)	Area (sq. in.)	
13,824	12	24	48.0	24	48.0	1152	1152
13,824	24	24	24.0	24	24.0	576	576
13,824	36	24	16.0	24	16.0	384	384
13,824	36	12	32.0	12	32.0	384	384
13,824	48	24	12.0	24	12.0	288	288
13,824	48	20	14.4	20	14.4	288	288

The data in Table 52 indicate the same relationship for the end frame load-bearing requirements as illustrated in Figure 33 for the end-load restraining requirements. A doubling of the length of the compaction chamber allows the load-bearing requirements for the end frame also to be reduced by one-half.

These findings are very significant in view of the direct correlation between load carrying capacity and material weight. The length of the compaction chamber is identified in the foregoing analyses as a prime factor governing the design of presses with minimum-weight frames. In terms of the press frame alone, the specifications for a solid waste compactor should emphasize as long a chamber and bale as possible.

For the total solid waste compaction process, however, the long-length criterion calls for balance in the relationship between (a) the pressure that has to be applied (b) the pressures transmitted, and (c) the

It would require an investigation of the interrelationships between several variables and tradeoff alternatives. Factors to be considered include:

- Over-all service-life requirements. For example, is the press to last 5, 10, or 20 years and operate 5, 6 or 7 days per week with 1, 2 or more shifts per day?
- The number of cycles per minute.
- The effects of various bale sizes. For instance, the handling of 100 tons of waste in 0.25-ton bales would require twice as many cycles as the compaction of the same tonnage into 0.50-ton bales.
- The characteristics and cost of the materials that could be used in the construction of suitable press frames, and
- The advantages and disadvantages of using more than one press for a given period of service life.

Accordingly, and because of the problem of technological obsolescence, it was decided that cycle life specifications for the rail-haul of solid wastes should be calculated on the basis of:

- a) A 10-year service-life
- b) Six working days per week
- c) A single 480 working minutes shift per day, and
- d) Two cycles per minute.

The calculations show that under these conditions a press frame should be capable of withstanding $10 \times 6 \times 480 \times 2$ or 2,995,200 cyclic load applications. This is the equivalent of a 5-year, 2-shifts-per-day operation at the same number of cycles per minute, and a 20-year, 1-shift-per-day operation at 1 cycle per minute.

Most installations should be well served by these cycle specifications. Installations, required to operate at a high level of production are more likely to gain from technological progress, such as improvements in press design than those facing less severe throughput demands. Furthermore, kinds of materials suitable for the press frame might make a 3-million cycle requirement equivalent to an unlimited service life in certain instances.

Evaluation of the total cycle implications must recognize again that the hydraulic compaction of solid wastes, as dealt with in this project, is not carried out by impact. The process, although fast perhaps in certain sub-operations, applies the pressure gradually and continuously throughout the total pressure range. In addition, the elasticity and high compressibility of the solid waste mixtures cause some cushioning in the load application. However, as indicated in Chapter III, II-6, appreciable peak forces nevertheless, can be developed, and these stresses must be considered in implementing the above cycle specifications.

VI. CONSIDERATIONS ON PRESS FOUNDATIONS

The foundation requirements for a compaction press are very important since they may constitute a controlling cost factor in the selection of a compaction site. Thus, the foundation requirements should be considered in the design of the compactor itself.

Within the scope of this project, it was not feasible to investigate the implications of press design alternatives in terms of self-contained or not-self-contained compaction units. A self-contained unit is defined as a press which does not require structures other than those provided by the press

itself for the containment of the forces developed during the compression process.

The wide variety of both local conditions and press alternatives suggest that the design and manufacture of self-contained presses might be less complicated than the implementation of not-self-contained presses. Therefore, it was decided to base the consideration of press foundations exclusively on factors associated with self-contained compaction units. The foundation requirements for these must embrace primarily the load to be carried, the shape or configuration needed, and cost. The governing factors, in turn, include the weight of the machine, the floor area requirements and the soil conditions.

The loading on the foundation is determined almost totally by the weight of the compaction unit. It should be recalled in this context that the hydraulic compaction of solid wastes is relatively slow and involves materials of relatively low stiffness. Thus continuous and/or major dynamic impacts are not likely to occur.

Furthermore, a single or multiple-axis compactor can be designed in such a way that all force applications take place in a horizontal plane. This will result in a relatively large foundation area, with, however, a relatively low area loading. The horizontal positioning of the axes of compaction eliminates the need for a pit or a complex shape of the foundation.

In contrast, compactors using a vertical arrangement of one compaction stage need a smaller foundation area. However, they do require perhaps a more complex foundation to support more of the total weight of the press on the smaller area. This, in turn, usually necessitates foundation reinforcements. Unfortunately, reinforcements for concrete, such as placed steel wire and bar reinforcements, are very expensive. Furthermore, the costs of foundation forms vary greatly, depending on soil conditions and the complexity of the foundation shape.

The specific foundation design for a compactor will, of course, require a detailed analysis for each specific set of parameters. The general arguments made above permit conclusions adequate for the first phase of the APWA rail-haul project but not sufficient for the implementation of demonstration projects.

In general, the foundation analyses suggest that solid waste compaction should preferably take place in the horizontal plane. If a choice has to be made between (a) land acquisition opportunities and/or cost and (b) foundation cost, the press should be designed to avoid the construction of a pit. This, in

turn, suggests that if compaction is to take place in the vertical plane, the compression forces should be applied from above.

SECTION TWO—SELECTED COMPACTION EQUIPMENT PERFORMANCE SPECIFICATIONS

The term "performance", as used in this section, refers to the functions the compaction unit has to complete to produce bales suitable for rail-haul. It does not address itself to the specific elements of press design needed to execute the compaction functions.

The information in this report provides a variety of inputs for establishment of compaction equipment performance specifications, and suggests that ultimately several sets of specifications may be developed.

Variables in local conditions have been identified as significant factors in drafting appropriate specifications. Selection of process capabilities must mesh with the local solid waste disposal objectives, input materials, and the chosen type of operations.

Within the scope of this project a framework could not be developed for even the major specification series possible. Nor was it feasible to develop more than one highly general specification example. It is suggested that additional specification work be done in the context of demonstration project developments, which are scheduled for the second phase of the APWA rail-haul study.

After evaluation of the data already discussed, it was decided to draft the specification example for a press producing a bale of about 0.50 cubic yard in the compaction chamber. Covering only the functional compaction performance requirements of the press unit in general, this example covers:

Materials to be compacted:

heterogeneous mixtures of solid waste materials which behave like semi-elastics under compaction.

Press loading:

by fast gravity-fill batch system, delivering the input charge in less than 5 seconds.

Volume Reduction ratio:

18:1

Pressure applied during final compaction stage:

2,000 psi

Pressure hold time:

15 seconds at 2,000 psi

Total cycle time:

1 minute

Service life:

total number of cycles—2.9 million.

Bale volume in the compaction chamber:

13 to 16 cubic feet, average 14 cubic feet.

Weight of bale in the compaction chamber:

as a rule, between 1,200 and 1,400 pounds

Dimensions of bale in the compaction chamber:

25.7 x 27.7 x an average of 34.0 inches and slightly variable.

Direction of pressure application for multi-stage presses in reference to bale dimensions in the compaction chamber:

Double-axis press:

25.7 inches = fixed

27.7 inches = parallel to direction of pressure application by 1st ram.

34.0 inches = parallel to direction of pressure application by 2nd ram (final pressure application)

Triple-axis press:

25.7 inches = parallel to direction of pressure application by 1st ram

27.7 inches = parallel to direction of pressure application by 2nd ram

34.0 inches = parallel to direction of pressure application by 3rd ram.

Special provisions:

locks needed to keep the rams not applying the final pressure in their fully extended position during the final pressure application, including any pressure hold time.

The dimensions for the compaction chamber were derived by combining the bale size postulates identified in Chapter II of this report with the findings on springback presented in Chapter III.

Springback in the direction of the final pressure application averages about 50 percent. Thus, the bale dimension pegged at about 34.0 inches in the compaction chamber will grow to about 51.0 inches after springback.

For this press specification, it was assumed that the bales would be loaded in the rail car two rows in height and that bale height would refer to the bale dimension parallel to the direction of the final pressure application. As a result, the total height of the lading in the rail car would average about 102 inches, which complies with loading height limitation of 108 inches.

Springback, in respect to the other dimensions, as shown in Chapter III, always was found to be least in the direction of the lowest pressure application. It

amounted, in the experiments, to about 5 percent for the first ram pressure application, and 10 percent for the second. Thus, the 25.7 inch compaction chamber bale dimension would grow to about 27 inches after springback, if a similar configuration for the press and the pressure application were used. This is the equivalent of the 2.25-foot bale side identified in Chapter II among the alternatives suitable for the width of the rail car.

As a result, this sample specification assumes that the bales would be loaded four in a row to fill the width of the car, which is about 9 feet. The first compaction chamber dimension was selected to correspond to the 2.25-foot bale dimension, because the amount of springback was always found to be least, and also vary the least, in the direction parallel to the lowest pressure application.

Thus, least amount of variation in the directional orientation of the springback is matched to the dimension in the bale loading configuration which, as outlined in Chapter II, is critical as applied to both rail car design and lading.

In addition, the press specifications as given in this example can be used to determine the length of a solid waste rail car. An average springback of 10 percent in the remaining 27.7-inches bale compaction chamber dimension would result in a bale dimension of about 30 inches. Since eight bales, stacked as stated above and weighing about 1,300 pounds each, would have a total weight of 5.2 tons, it would take 19 to 20 rows of bales to make up a load of 100 tons. In turn, the loading space in the rail car would have to be about 600 inches (20 bales x 30 inches each) or about 50.8 feet long.

The specification of 2,000 psi of applied pressure and a 15-second pressure hold was chosen for several reasons. First, compaction with 2,000 psi of applied pressure appears, as shown in Chapter III, sufficient to produce stable bales for the compaction chamber size given. Second, the addition of the 15-second pressure hold at 2,000 psi can produce bale characteristics equivalent to those achieved at about 2,500 psi of applied pressure without a pressure hold. Thus, the 15-second pressure hold will provide an added margin of safety in achieving the compaction objectives.

Third, the tests suggest that compaction of solid waste mixtures with an appreciable amount of moisture is better at 2,000 psi than at higher pressure application, and retains more moisture. The possibility of moisture and pulp blowoffs under these conditions is also reduced.

Over-all, the press specifications appear well suited to the solid waste rail-haul requirements

outlined in Chapter II. It is hoped that all the data will encourage press manufacturers to establish additional specifications and develop widely applicable solid waste compaction equipment.

SECTION THREE—PRICES AND CONSTRUCTION COST ESTIMATES FOR HYDRAULIC PRESSES POTENTIALLY SUITABLE FOR THE HIGH PRESSURE COMPACTION OF SOLID WASTES

Solid waste disposal, as pointed out in Chapter II, is highly sensitive to costs. Moreover, a high pressure solid waste compaction process will have to compete with many alternate methods of disposal.

A striking relationship seems to exist between the number of potential process installations and the amount of the unit price. In broad terms, a decrease in the press unit price causes a disproportionate increase in the total press sales volume. The smaller the community, governmental jurisdiction, or transfer station service area, the greater is the importance of low equipment price.

It should be stressed that governmental jurisdictions are more often medium-sized or small, even if located in a metropolitan area.

1. DATA LIMITATIONS

The information offered here can present only an approximate estimate of press prices and construction costs. More precise information was not readily available, nor did it come within the limitations of this project. A myriad of factors, interrelationships and tradeoffs must be considered in applying value engineering techniques to press design and construction.

All the following information is based on quotes and cost studies accessible to the project team. Although most of this is classified as preliminary in nature, it is considered reasonably accurate by those who supplied it.

The estimates are confined to hydraulic presses. Since these presses are expected to be the primary element in the first generation of solid waste compaction equipment, their prices may serve as a reasonable indicator in comparing the economics of competitive processing methods.

The data present the direct investment cost or straight purchase price as well as the energy cost. They do not include the cost for the foundations, transport of the press to the site of operations, and installation, nor any personnel, maintenance or supply expenditures.

The information can serve as a broad guideline to:

- a) assist decision-makers in government and

- industry in the initial planning for the rail-haul of solid wastes, and
- b) help in allocating responsibilities for preparation and implementation of bid specifications which always are costly and time consuming for both government and industry.

II. PRICES AND COST OF EXISTING HYDRAULIC PRESSES

Some guidelines on prices and costs can be established for this analysis by an investigation of presses already on the market and roughly suitable for the compaction of solid wastes.

Certain of the data obtained in this investigation are summarized in Table 53 on the following page. The press examples given include entries from most of the major metal scrap baler manufacturers.

It must be stressed in the presentation that with the exception of entry "F," none of the presses originally was designed for the compaction of solid wastes. Only entry "F" gives data from a firm proposal for the sale of a solid waste compaction press. However, all the other presses could be used for compaction if necessary.

Significantly, none of the presses, including entry "F," would be designed as is for such compaction. For example, the volume reduction ratio of the press in entry "F" is substantially too low if a bale of 2.0 cubic yards is to be produced, while the volume reduction ratios for entries "A" to "E" sometimes are substantially too high for the bale sizes indicated. Some of the pressures are too low for the size of the bale, excluding holding time, while others are too high.

Furthermore, the power costs quoted are judged to be high. The full power is used, as a rule, only during a relatively short portion of the compaction cycle. For a given period of time, the actual power consumption is frequently calculated to be 35 to 40 percent of the total horsepower installed. However, in the absence of (a) any detailed backup data on the actual power consumption, and (b) specific investigations to gauge the time-power needs of the compaction, it appeared advisable to use a higher power demand factor.

Despite these critical comments, the data in Table 53 suggest that the high pressure compaction of solid waste promises extremely attractive economics as well as basic performance capabilities. Assuming a properly designed press, the data support the APWA rail-haul interim report in estimating that compaction

may cost less than 40 cents a ton, including depreciation, maintenance and power.

III. COST ESTIMATES FOR A LIGHTWEIGHT FRAME SOLID WASTE COMPACTION PRESS

The following cost estimates for a lightweight frame, solid waste compaction press are based on IITRI experience in the design and construction of its large, high pressure evaluation vessel. The relatively well-documented IITRI costs were used to help project solid waste compactor costs in terms of different bale sizes in the compaction chamber.

Thus the cost estimates given represent the experience of only one approach to the design and construction of a lightweight press frame. Other approaches obviously are possible and most likely will result in different cost estimates.

As mentioned before, the IITRI approach was chosen for this analysis because it represents the best documented examples available within the constraints of this study.

As pointed out previously, the engineering of a press is estimated to take as much as 3,000 to 4,000 manhours. More time obviously would be required for the development of a new prototype press, since many variables and tradeoff alternatives must be established and evaluated carefully.

Over-all, the cost estimates presented might be considered the approximate minimum for presses of the same compaction chamber bale dimensions. It might be recalled that the IITRI design, although incorporating a safety factor of 2.0 to 2.5, has an attractively low weight-to-force ratio for its frame structure. This is significant since press frames may account for as much as 40 percent of the total weight of existing presses potentially suitable for the compaction of solid wastes.

The estimates were made for single- and double-axis compactors and various sizes of cubic bales ranging from 0.3 to 1.0 cubic yard in the compaction chamber. It was discreetly assumed that a final pressure of 3,500 psi would be applied to the bale and that a volume reduction ratio of 18:1 would be required. Finally, the frame weight calculations were made to differentiate between standard and lightweight end frame sections as evolved from the IITRI experience.

Based on the IITRI strap frame design and construction experience and the specific materials used, the calculated frameweights are shown in Table 54.

TABLE 53
Summary of Economic Data on Hydraulic Presses Potentially Suitable
for the Compaction of Solid Wastes

Press Specifications and Evaluation Parameters		Hydraulic Press Examples					
		A	B	C	D	E	F
DESCRIPTION OF PRESS							
<u>Charging Box Dimensions</u>							
a) Configuration	(inches)	24x48x96	37x58x150	48x72x144	40x50x116	60x80x280	51x90x168
b) Cubic Feet	(number)	64	186	288	134	777	446
c) Cubic Yard	(number)	2.37	6.88	10.66	4.96	28.77	16.52
<u>Bale Dimensions</u>							
a) Configuration	(inches)	14x14x22	24x16x35	24x22x48	14x14x24	24x24x24	36x36x72
b) Cubic Feet	(number)	2.49	7.77	14.66	1.58	8.00	54.00
c) Cubic Yard	(number)	0.09	0.29	0.54	0.06	0.30	2.00
<u>Theoretical Volume Reduction Potential</u> <u>In Terms of Press Dimensions as Given</u> <u>by Sizes of Charging Box and Bale</u>							
	(ratio)	26:1	24:1	20:1	82:1	96:1	8:1
<u>Compaction Process</u>							
a) Number of compaction stages		2	2	2	3	3	2
b) Pressure applied to materials							
ba) first stage	(psi)	262	272	233	95	106	740
bb) second stage	(psi)	1475	1620	1350	685	735	2180
bc) third stage	(psi)	-	-	-	2450	2460	-
c) Total force applied on the ram in the final compaction stage (tons)		227	452	716	240	707	1700
d) Operating time and production							
da) cycle time	(minutes)	2.4	3.0	2.5	0.6	1.5	1.6
db) bales per hour	(number)	25	20	24	100	40	36
dc) provision for pressure holding time		none	none	none	none	none	none
<u>Hydraulic Parameters</u>							
a) Capacity of Pumps	(gpm)	216	432	752	325	565	N.A.
b) Size of fluid reservoir	(gallons)	575	1200	4000	N.A.	N.A.	N.A.
c) Power supply							
ca) type		electric motor	electric motor	electric motor	electric motor	electric motor	electric motor
cb) capacity	(hp)	75	150	400	210	410	500
<u>Overall Press Dimensions</u>							
a) Configuration of floor area	(feet)	23x23	31x26	38x32	30x27	27x59	26x43
b) Shipping weight	(pounds)	75,000	176,000	280,000	100,000	465,000	390,000
c) Plane of operations		horizontal	horizontal	horizontal	horizontal	horizontal	horizontal
Purchase Price F.O.B. Factory	(dollars)	40,000	84,000	165,000	93,500	265,000	300,000
SELECTED PRESS COMPARISON AND EVALUATION DATA							
1. Production of solid waste bales based on a material density in the compaction chamber of							
a) 90 lbs/cuft at 2000 plus psi applied pressure,	(tons/hr)	-	-	-	7.11	14.40	87.48
b) and 80 lbs/cuft at 1000 to 1500 psi applied pressure	(tons/hr)	2.49	6.22	14.07	-	-	-
2. Price per pound of shipping weight	(dollars)	0.53	0.47	0.59	0.93	0.57	0.77
3. Price per ton of hourly production	(dollars)	16,064	13,505	11,727	13,150	18,403	3,430
4. Price per ton at 18,200 hours of production [7 hrs/day, 5days/wk, 52wks/yr, 10 yrs]	(dollars)	0.88	0.74	0.64	0.72	1.01	0.19
5. Price per ton at 36,400 hours of production [20 yrs]	(dollars)	0.44	0.37	0.32	0.36	0.51	0.10
6. Price per horsepower	(dollars)	533	559	413	445	645	600
7. Power cost per hour at a 60% utilization of the installed horsepower capacity and 1-1/2 cents per kilowatt hour	(dollars)	0.50	1.00	2.68	1.41	2.75	3.36
8. Power cost per ton of hourly production	(dollars)	0.20	0.16	0.19	0.20	0.19	0.04
9. Total direct compaction process cost, 20-year service life	(dollars/ton)	0.64	0.53	0.51	0.56	0.70	0.14

The data given in Table 54 show that a replacement of the standard end sections by lightweight end sections reduces the total frame weight by 22 to 26 percent. The data also indicate that the addition of a second compaction stage reduces the frame weight by 36 to 42 percent as compared to a single-axis compaction press.

The frame weights given in the above table were used for the press cost estimates by employing the following relationship:

$$C_T = \frac{C_W W_T}{W_f}$$

where

C_T = the total cost of the press

C_W = the cost per pound of material

W_T = the total weight of the frame, and

W_f = the fraction of the total frame weight in terms of the total weight of the press.

In gauging the estimate patterns, it was assumed that the fraction of frame weight to total press weight would vary from 25 to 40 percent. The basis was that the weight of the frame itself would decrease while the weight of the hydraulics and other press components would remain constant.

In addition, two prices per pound of material—\$1.00 and 75 cents—were introduced into the calculations. This selection is based on data established earlier for existing compaction presses. Thus, the estimates reflect the cost experience with presses produced in quantities greater than one. The

cost undoubtedly will be higher for a prototype press, if the expenditures for the conceptual design, engineering and any special tooling are included.

The end results of all the calculations are summarized in Table 55 on the following page. Here are examples of how the development of a lightweight frame, hydraulic solid waste compactor might promise extremely attractive investment economies. For example, at an over-all material cost of \$1.00 per pound, a 0.6-cubic yard bale in the compaction chamber, a standard end section, and a frame weight representing only 25 percent of the total press weight, a double-axis lightweight frame compactor might cost approximately \$104,000. This is, within the context of this study, the tentative order of magnitude if a cost/price indicator is to be given.

To place these cost estimates into perspective, it must be recognized that for a 20-year useful service life the direct depreciation cost for this compactor amounts to \$5,200 a year. At a production rate of just 1 bale per minute, an average density of 1 ton per cubic yard in the compaction chamber and an effective production time of 7 hours per day for only 5 days per week and 52 weeks per year, this compactor would process 7 x 60 x 5 x 52 x 0.6, or 65,520 tons of solid wastes per year. Thus, excluding interest cost and return on investment, the direct depreciation charges for the press would amount to only \$0.079 per ton.

TABLE 54
Estimated Lightweight Frame Weights for Single- and Double-Axis
Solid Waste Compactors, Based on Different Bale Sizes, Two Types of End
Section Construction, a Cubic Configuration of the Bale in the Compaction
Chamber, and an 18:1 Volume Reduction Ratio.

Type of Compactor	Bale Size (cubic yards)	Total Frame Weight*	
		Standard End Sections (tons)	Lightweight End Sections (tons)
Single-Axis	0.3	11.1	8.2
	0.6	21.4	18.0
	1.0	38.5	30.0
Double-Axis	0.3	7.1	5.4
	0.6	13.0	10.7
	1.0	22.2	17.3

Source: IIT Research Institute

* Data slightly rounded

TABLE 55
Cost Estimates for Lightweight Solid Waste Hydraulic Compaction Presses Based on
Variations in Bale Sizes, End Sections, Ratios of Frame Weight to Total Weight,
Number of Compaction Stages and Material Cost

Type of Compactor	Bale Size (cu.yds.)	Cost Estimate for Total Press*									
		Standard End Section					Lightweight End Section				
		Total Weight of Frame (tons)	Percent of Frame Weight of Total Weight 40%	30%	25%	Total Weight of Frame (tons)	Percent of Frame Weight of Total Weight 40%	30%	25%		
		(dollars)	(dollars)	(dollars)	(dollars)	(dollars)	(dollars)	(dollars)	(dollars)	(dollars)	(dollars)
a) Cost Estimates Based on an Overall Material Cost of \$1.00 per pound.											
Single-Axis	0.3	11.1	55,500	74,000	88,800	8.2	41,000	54,700	65,600		
	0.6	21.4	107,000	142,700	171,200	18.0	90,000	120,000	144,000		
	1.0	38.5	192,500	256,700	308,000	30.0	150,000	200,000	240,000		
Double-Axis	0.3	7.1	35,500	47,400	56,800	5.4	27,000	36,000	43,200		
	0.6	13.0	65,000	86,700	104,000	10.7	53,500	71,400	85,600		
	1.0	22.2	111,000	148,000	177,600	17.3	86,500	115,400	138,400		
b) Cost Estimates Based on an Overall Material Cost of \$0.75 per pound.											
Single-Axis	0.3	11.1	41,700	55,500	66,600	8.2	30,800	41,000	49,200		
	0.6	21.4	80,300	107,000	128,400	18.0	67,500	90,000	108,000		
	1.0	38.5	144,400	192,500	231,000	30.0	112,500	150,000	180,000		
Double-Axis	0.3	7.1	26,700	35,500	42,600	5.4	20,300	27,000	32,400		
	0.6	13.0	48,800	65,500	78,000	10.7	40,200	53,500	64,200		
	1.0	22.2	83,300	111,000	133,200	17.3	64,900	86,500	103,800		

*Data slightly rounded

The data presented in Table 55 lend themselves to numerous cost/performance calculations of the type just described. Combined with other data given in this section and other parts of the report these cost estimates indicate that high pressure compaction of solid wastes is feasible. This is particularly true if lightweight frame press designs are utilized since they have substantial advantage both in terms of investment and operating cost.

SECTION FOUR—IMPLICATIONS OF THE HIGH PRESSURE COMPACTION OF SOLID WASTES WITH RESPECT TO RAIL-HAUL

In the rail-haul of solid wastes, the use of high pressure compaction must be viewed in terms of the three major system building blocks. As indicated in the APWA rail-haul interim report, these building blocks are (1) the transfer stations, (2) the rail transport link, and (3) the sanitary landfills. Also as indicated in that report, public health and environmental control are of substantial consideration in each of these building blocks as well as the system as a whole.

Since a detailed discussion of the implications is planned for the final report on that rail-haul study, the concern here is with rail-haul development benchmarks rather than specific parameters for the equipment and operations.

Generally, this report should provide sufficient information to gauge the influence of variables critical to applying high pressure compaction to solid-waste rail-haul. However, this project permits the major variables to be outlined only in an indicative rather than definitive way.

I. OVER-ALL PUBLIC HEALTH AND ENVIRONMENTAL CONTROL ASPECTS

The combination of high pressure compaction and rail-haul tends to reduce the pollution burden to the environment, as contrasted to other commonly used solid waste disposal process, especially in the absence of pollution controls. Moreover, the compaction process and rail-haul require a lesser quantity and sophistication of pollution control equipment than some of the other waste disposal processes.

Finally, there is substantial indication that the high pressure compaction process itself not only avoids causing pollution but can be developed through further research into a valuable tool for environmental control.

II. THE IMPLICATIONS WITH RESPECT TO TRANSFER STATIONS

The implications covering transfer stations for the rail-haul of solid wastes can be summarized briefly as follows:

1. Foundations

The utilization of high pressure compaction equipment will not, as a rule, necessitate the construction of a pit under the press.

A press may weigh from about 50 to 150 tons and require a maximum floor area of about 1,300 square feet.

The specific foundation requirements, as indicated previously, will have to be worked out in terms of a given installation or demonstration project.

2. Pretreatment of the Solid Waste

Input Materials

As a rule, residential, commercial and general industrial solid waste materials as collected by normal, properly operated collection systems, can be compacted and baled successfully. No pre-treatment of the input materials is required in such cases.

However, as indicated in Chapter III rubber tires must be excluded unless they are shredded and reduced to small pieces of perhaps 1 to 2 cubic inches.

Implications must be considered for route layouts in certain collection systems, such as exclusive service of commercial districts and suburban residential settlements. Care must be taken to prevent certain components from representing too large a portion of the mixture making up an input charge. This applies especially to vegetable or garden type wastes and dirt.

Furthermore, solid wastes heavily wetted by rain cannot be compacted into a stable bale without the use of aids producing the required stability. But generally a light mixing of the solid waste materials prior to charging the press may be all that is needed for adequate preparation of the solid waste input.

The conditions existing at a given transfer station will, of course, determine both the pre-treatment method and the amount of any necessary pre-treatment. Preliminary investigations made for the APWA rail-haul project suggest that inexpensive methods already are available and appear to be adequate.

3. Press Loading Equipment

The amount of solid waste material input normally is to be controlled by weight only. This is one of the major findings of this project, which has proven that input control by volume is detrimental to

a rational process design and that a weight/volume input control is unnecessary.

For high throughput operations, the press loading equipment should be capable of charging the press by a gravity-fill batch system with about 1,400 pounds of solid waste materials in less than 5 seconds, once every minute.

The performance requirements are less demanding for transfer stations handling fewer than 250 tons per shift.

To correspond to the press specifications for a given transfer station, the press loading equipment will have to be determined ultimately in terms of a demonstration project.

4. Handling of the Bales

Almost all of the existing material handling methods are well suited to the transport of bales in the transfer station, the movement to and from any storage area, and the loading of the rail cars.

However, a slight amount of material spillage will occur, particularly if the bales are made from refuse charged into the press in a loose state and not contained in paper sacks. The findings of this project suggest that the spillage from bales of loose wastes amounts to less than 1 percent of the total weight of the materials processed. An inclusion of oversized metallic solid waste items in the input mix, or use of paper sacks in the collection system, will reduce this percentage substantially.

5. Storage of Bales

The bales are suitable for any length of storage that might be contemplated within the context of currently envisioned rail-haul systems.

The specific height of the bale storage must be gauged to the rail car loading configuration. The findings of this project indicate that bales can be stored at least 8 to 10 feet high without any load carrying supports.

Provisions should be made for ventilation of the storage area. However, high capacity ventilation equipment is not required. A slight natural draft, obtainable through proper design of the building, apparently is sufficient.

6. Public Health and Environmental Control

To assure proper industrial hygiene and working conditions, the transfer station area housing the compaction process must be provided with active ventilation to be used as needed.

In addition, the area around the charging box and the compaction chamber of the press requires a drainage system and treatment for the runoff of any leachants. This system should be capable of handling,

on the average, a maximum of 2 quarts of runoff per ton of materials processed.

The parts of the press and transfer station in contact with the solid waste materials and particularly the leachants must be cleaned at regular intervals.

7. Cost

In terms of the press only, it will cost an average of 40 to 50 cents to compact 1 ton of solid waste materials. These figures exclude finance charges such as interest foundations and labor, to allow for local conditions and arrangements. In some instances the press may operate automatically; in others a press operator may be required. The total owning and operating cost for a compaction process-transfer station will be developed in the final report of the first phase of the APWA rail-haul study.

III. THE IMPLICATIONS WITH RESPECT TO RAIL TRANSPORT

The implications for rail transport in terms of rail car design; the bale loading configurations, and the direct rail transport are summarized as follows:

1. Bale Loading Configurations

It is possible to design many configurations for the loading of bales on a rail car. In terms of the bales, almost any loading configuration can be implemented successfully.

As a result, the specific bale loading configuration can be determined almost entirely in terms of the rail-haul system operations developed for a demonstration project, including the selection of rail cars and loading equipment.

2. Rail Car Design

The rail car should be covered primarily for reasons of public relations, but also for reasons of environmental control. As shown in Chapter IV, exposure to the elements apparently has no appreciable effect on the stability characteristics of the bales. However, in cases of rain, the accumulation of water in the rail car might be disadvantageous. Also an open car, especially if it has to stand in a station for long during warm weather, may attract flies or other insects.

The rail car should be designed to facilitate the loading and unloading of the bales in sets. Thus, an all-door boxcar appears to be most suitable for the rail-haul of solid wastes.

In addition, the car design must be integrated with the material handling methods chosen, or vice versa. For example, the car floor might have to be grooved to permit the loading and unloading of bale

sets by heavy industrial fork-lift trucks.

It would be advantageous for the car to have movable bulkheads to assure a tight fitting load, as variations in the bale dimensions occur. In all door cars these movable bulkheads preferably might be placed in the center to achieve maximum effect and enhance the cost-performance ratios as applied to the car structure.

Also, the doors might be hinged to provide about 1 inch of additional clearance for their "move" position as compared to their "closed and locked" position. Thus, if the bales should shift or expand during transport, any possible jamming caused by friction between the bale surfaces and the door would be avoided when the doors are opened.

The stability experiments suggest that solid waste rail cars do not need more than the normally required spring systems to cushion the lading against vibration and shock.

Ventilation of the car would be beneficial. However, force ventilation devices are not required. A simple circulation of outside air through the car is sufficient, particularly if the amount of air admitted and exhausted can be controlled in accordance with seasonal temperature changes.

3. Transport Operations, Distance and Routing

All railroad operations, as commonly performed today, are well suited to the shipment of solid waste bales. These include the switching, classification, train assembly, and over-the-road travel.

Compacted solid waste bales can be shipped for long distances. Thus interstate solid waste rail-haul networks can be set up where necessary or desirable. Routing alternatives and condition of infrequently used tracks do not appear to be significant considerations in the selection of a specific transport configuration.

Thus, solid-waste rail-haul networks can be designed exclusively on the basis of maximum efficiency for the movements involved.

IV THE IMPLICATIONS WITH RESPECT TO SANITARY LANDFILLS

The implications of placing solid waste bales compacted at high pressures in sanitary landfills are viewed in reference to the construction and operation of the landfill as well as the on-site environmental control measures.

1. The Basic Construction of Sanitary Landfills for the Disposal of Solid Waste Bales

Placement of highly compacted solid waste bales into sanitary landfills requires basic landfill construction specifications of the same order as those

for unbaled and/or less compacted refuse.

Provisions for the escape of gases might have to be made. Drainage installations required for the removal of leachants or seepage need not have the same capacity as those required for ordinary landfills of comparable size, since highly compacted solid waste bales resist water percolation more than less compacted wastes. Provisions for rain water runoff must, of course, be made and should follow the normal landfill experience in a given location.

Generally, the specific landfill construction will have to be determined in terms of a given case or demonstration project, and some significant tradeoff alternatives must be considered. For example, the requirements for roads in the landfill depend upon factors such as the weight of the bale loads transported, the total volume of wastes disposed of, the landfill depth, the location of the railroad siding, the method of on-site bale transport, the soil conditions, and the availability of cover material.

In evaluating the basic construction implications, it should be recognized that highly compacted solid waste bales allow for a much better use of available landfill space than is common with current methods. Solid waste bales permit an increase in the space utilization by about 60 to 90 percent, since they could average from 1,600 to 1,900 pounds per cubic yard as compared to a maximum density of about 1,000 pounds in most of the existing landfills where loose refuse is buried.

2. Operations of Landfills for Solid Waste Bales

The operations landfills for solid waste bales differ in several respects from existing landfill operations.

First, solid waste bales do not require on-site compaction. Second, the bales must be transported from the rail head to the actual disposal spot. Third, fullest use of the available space calls for a placement of the bales by stacking or an equivalent method.

The establishment of detailed cost-performance parameters requires, of course, both the specification and analysis of the needed equipment implementation. Examples of such an evaluation are given in the first phase report of the APWA rail-haul study.

3. Public Health and Environmental Control Measures

In terms of environmental control, solid waste bale landfills appear to have distinct advantages over existing landfills.

First, there is much less chance for papers to be blown around in high winds. Second, solid waste bales do not burn as easily as uncompacted waste

materials. Third, should smoldering fires occur in a bale fill, they possibly would not be as severe as those in existing landfills because the presence of oxygen is reduced. And fourth, there is less chance for odors to escape, since less of the material is exposed to surface winds than in landfills handling uncompacted wastes.

Over-all, the utilization of high pressure compaction as an integral part of sanitary landfilling offers the promise of eliminating many complaints stemming from lack of environmental control. Less emphasis has to be given to the care with which the operations are performed. In the high pressure solid waste compaction processes, most of the significant environmental control measures are built in automatically and not subject to human error or negligence.

V. CONCLUSIONS

Implications of high pressure compaction for the rail-haul of solid wastes could be evaluated and discussed only briefly within the scope of the present project.

The information strongly suggests not only that major difficulties can be avoided, but that substantial benefits can be gained.

It should be repeated that (a) selected details of the implementation are given in the report on the first phase of the APWA rail-haul project and (b) because of the numerous interrelationships and variables involved, the specifics can be quantified or judged only by actual cases and/or a demonstration project.

SECTION FIVE—OUTLOOK

The present project has demonstrated that the high pressure compaction of solid wastes may be ranked among the most attractive of solid waste disposal processes.

The results of this project suggest that additional testing and development might lead quickly and efficiently to substantial improvements. These investigations will reduce the lead time required to implement the installation of high pressure compaction systems.

Further process improvements must recognize that solid waste disposal represents a more complex system than is commonly supposed. The interrelationships among the manifold material, equipment and operation factors seem to demand a

comprehensive, well integrated pattern of research.

Specifically, the project findings suggest followup research on:

- a) Development of a lightweight press tailor-made for the high pressure compaction of solid wastes.
- b) Behavior of single solid waste components and different solid waste mixtures under varying compaction conditions.
- c) Behavior of "standard" solid waste mixtures under compaction conditions only touched upon in the present project.
- d) Compaction of exceedingly wet solid waste materials.
- e) Reduction of springback, and most important,
- f) Utilization of high pressure compaction as a positive tool for advanced environmental control.

In terms of total process development, all the above factors are closely interrelated. To tailor a lightweight press to solid waste compaction requirements, diverse material behavior patterns must be considered. Testing of unusual solid waste input mixtures might provide inputs that could enhance the application potential of compaction equipment. To enlarge upon the environmental control effects, different analyses on material behavior are required, and perhaps a different design of the press or compaction process.

In addition, the promise of process improvement offers a multiplication of benefits. A lightweight press is low-cost and thus might improve the operational options available to many solid waste disposal jurisdictions. The service life of many sanitary landfills might be more than doubled and substandard operations more easily eliminated. Solid waste bales might effect the reclamation of arid areas and turn the scars of ravaged land into topographic assets.

Further process developments promise to place solid waste disposal beyond a mere negative environmental control and transfer its efforts and funds to the category of resources. In view of this opportunity, it is recommended that additional efforts—estimated at about \$480,000 and one year of unencumbered work—be authorized as speedily as possible.